Physics motivations for sub-percent absolute cross sections

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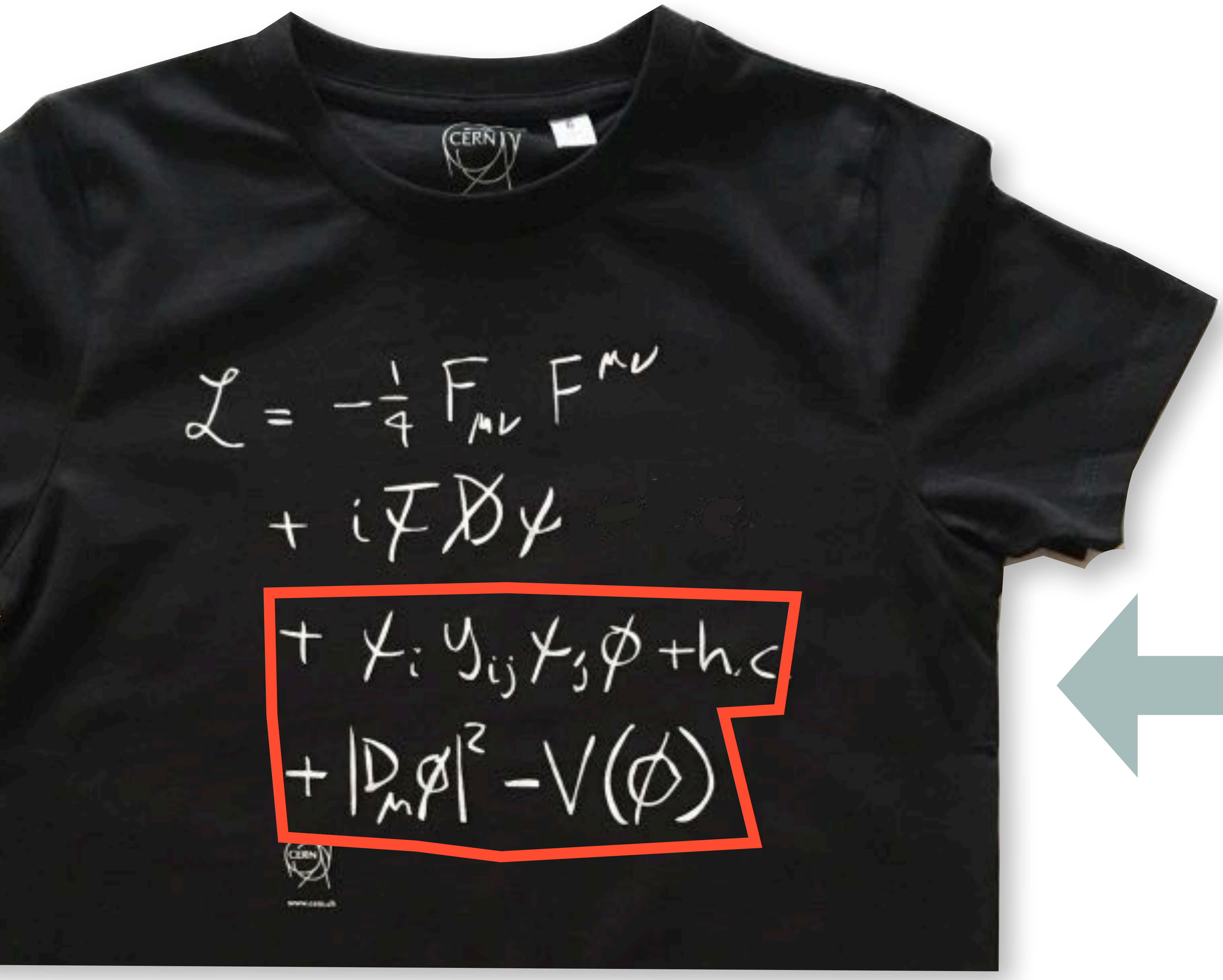
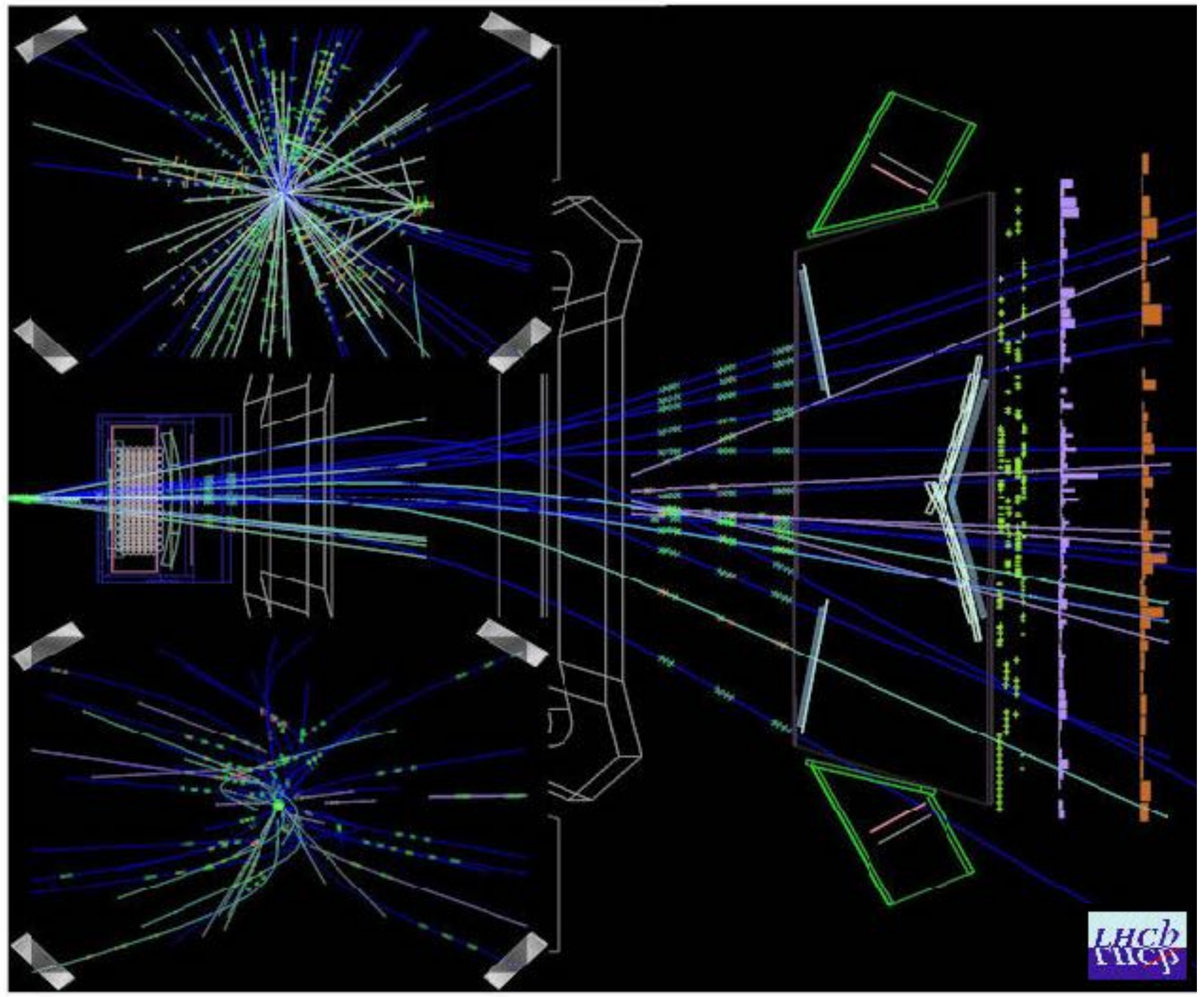
LHCb UK annual meeting,
University of Warwick, 4 January 2019

UNDERLYING THEORY

EXPERIMENTAL DATA



can we achieve sub-percent precision?

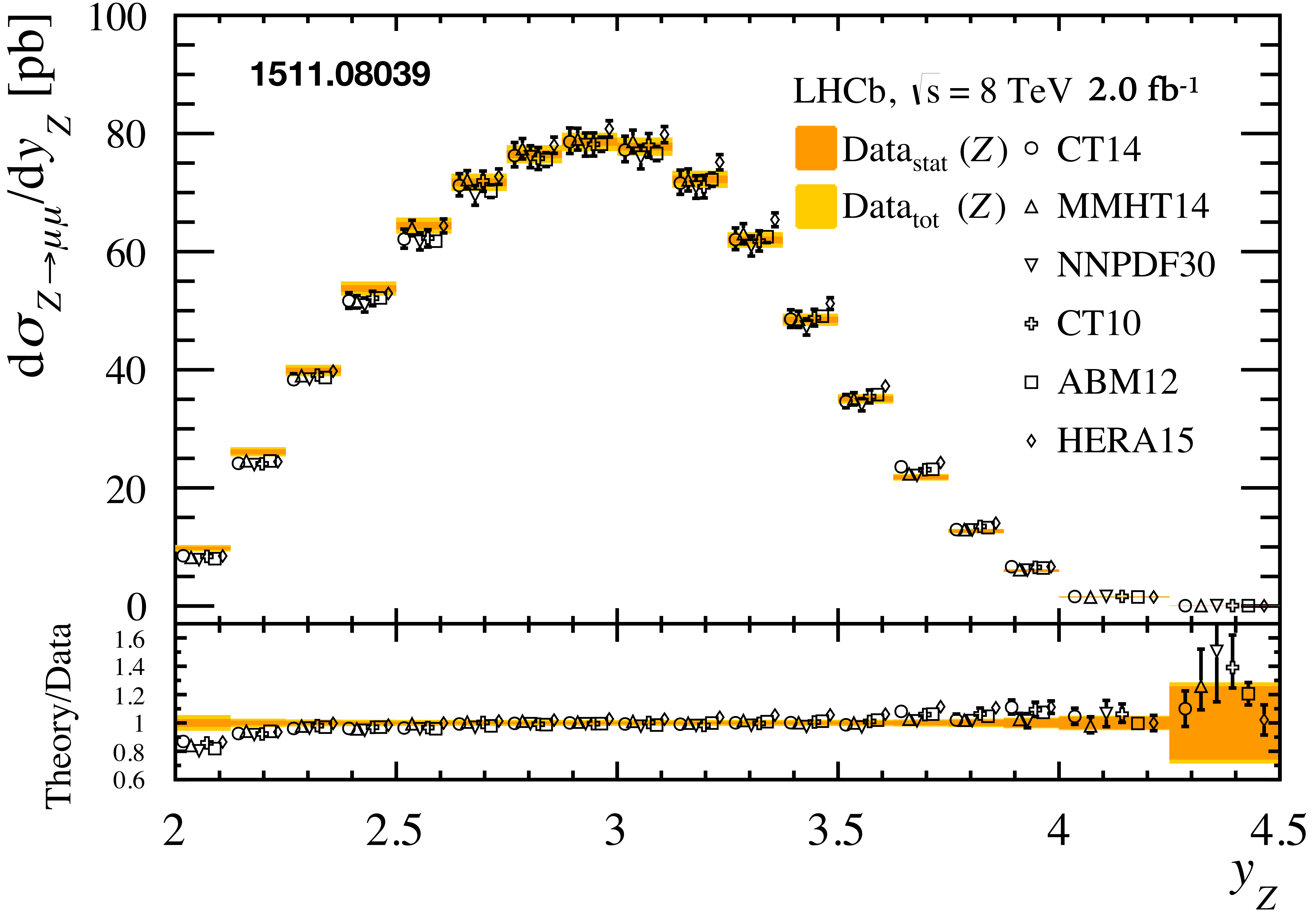


is it experimentally feasible?

LHCb precision

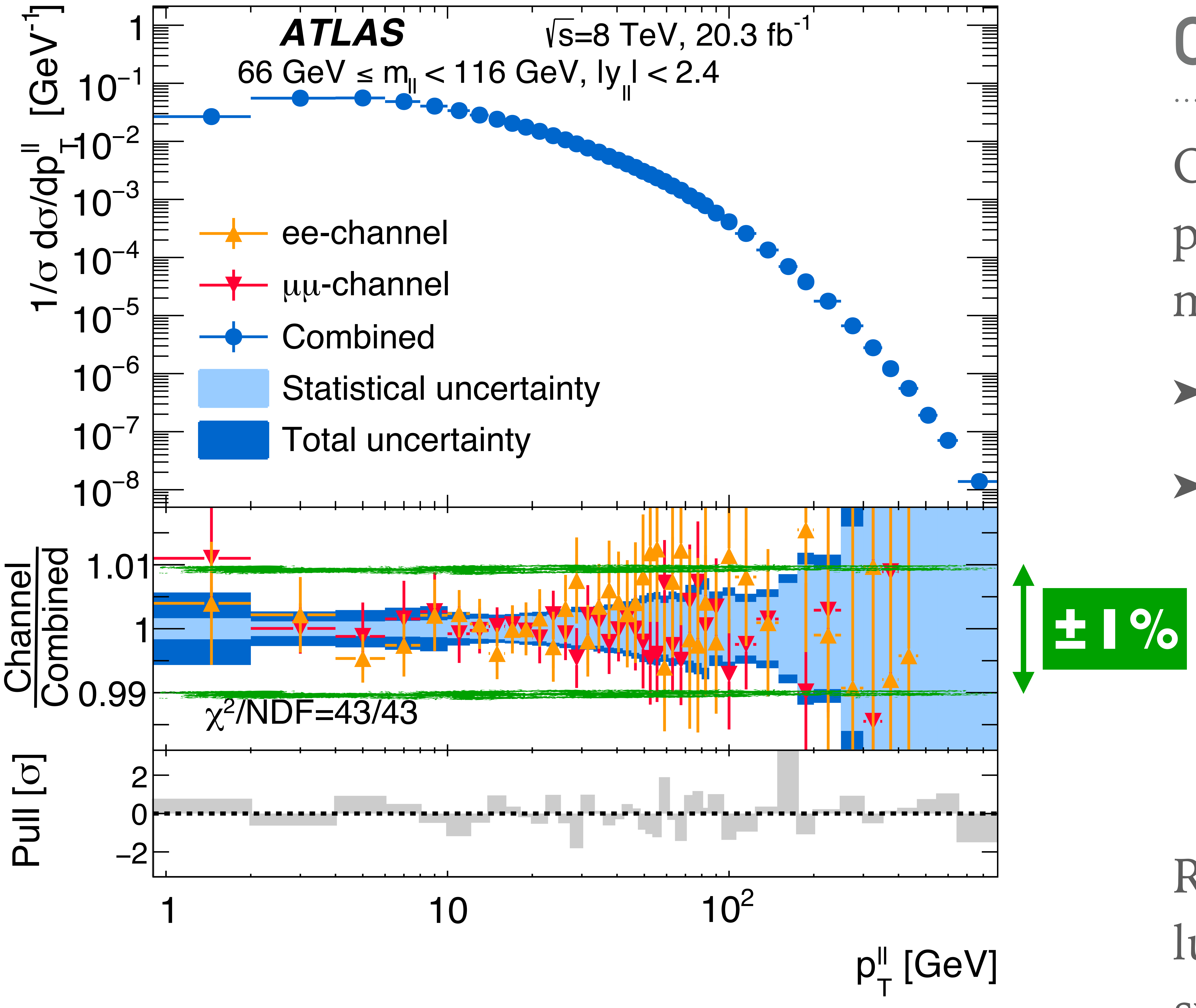
$$\sigma_{Z\to\mu^+\mu^-} = 95.0 \pm 0.3 \pm 0.7 \pm 1.1 \pm 1.1\,\text{pb}\,,$$

stat. syst. beam E lumi



LHCb achieves 0.8% uncertainty, aside from luminosity uncertainty

(beam energy systematic greatly improved since this paper)



Other experiments?

One of the most precise results are perhaps for the Z transverse momentum (ATLAS)

- ➤ normalised to Z fiducal σ
- ➤ achieves <1%, from p_T = 1 to 200 GeV, and <0.5% in some regions

Ratio to total cross section cancels lumi & some lepton-efficiency systematics.

One limiting factor: luminosity uncertainty

Experiment	ALICE	ATLAS	CMS		LHCb	
pp running period	2010	2012	2012		2012	
$\sqrt{s}$ (TeV)	7.0	8.0	8.0		8.0	
Absolute-calibration method	*vdM*	*vdM*	*vdM*	*vdM*	Combined	BGI
Calibration uncertainty $\Delta\sigma_{vis}/\sigma_{vis}$ (%)	3.5	1.2	2.3	1.47	1.12	1.43
μ or total–rate dependence (%)	-	1.4	< 0.1		0.17	
Long-term stability (%)	1.5	0.6	1.0		0.22	
Subtraction of luminosity backgrounds (%)	3.0	0.2	0.5		0.13	
Other luminosity-dependent effects (%)	1.5		0.5		-	
Total luminosity uncertainty (%)	5.0	1.9	2.6	1.5	1.2	1.5

→ Appdx

From LHCP 2016 talk by W. Kozanecki

LHCb can do ±1.1%. Can that be improved upon?

Other experiments have ~2% lumi uncertainty. Can new hardware help them match LHCb?

If LHCb remains the best, can its lumi uncertainty be transferred to other experiments (e.g. J/ψ & $Z \to \mu\mu$ measurements)

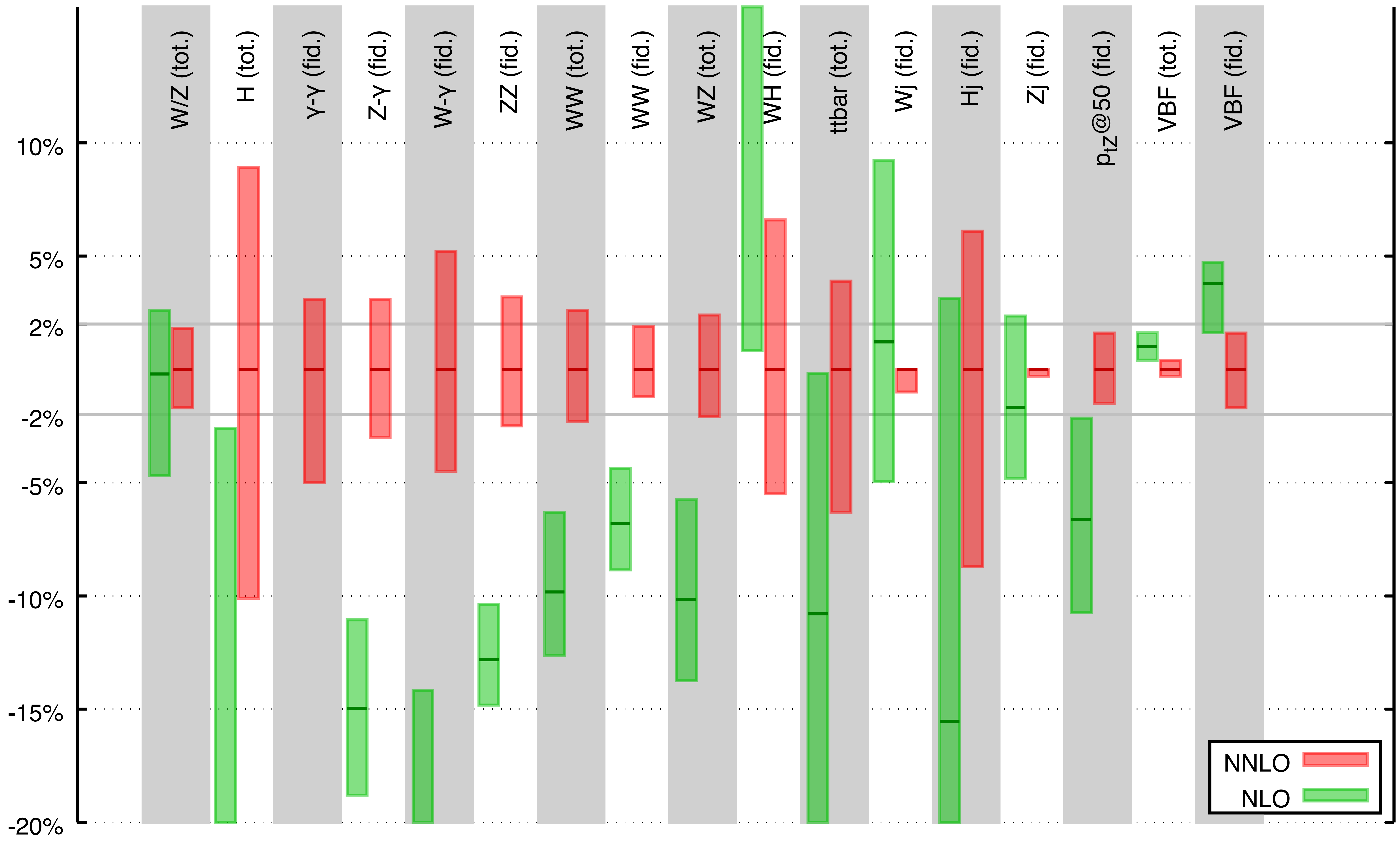
luminosity is potential *keystone measurement* for LHC precision programme

is QCD theory up to it?

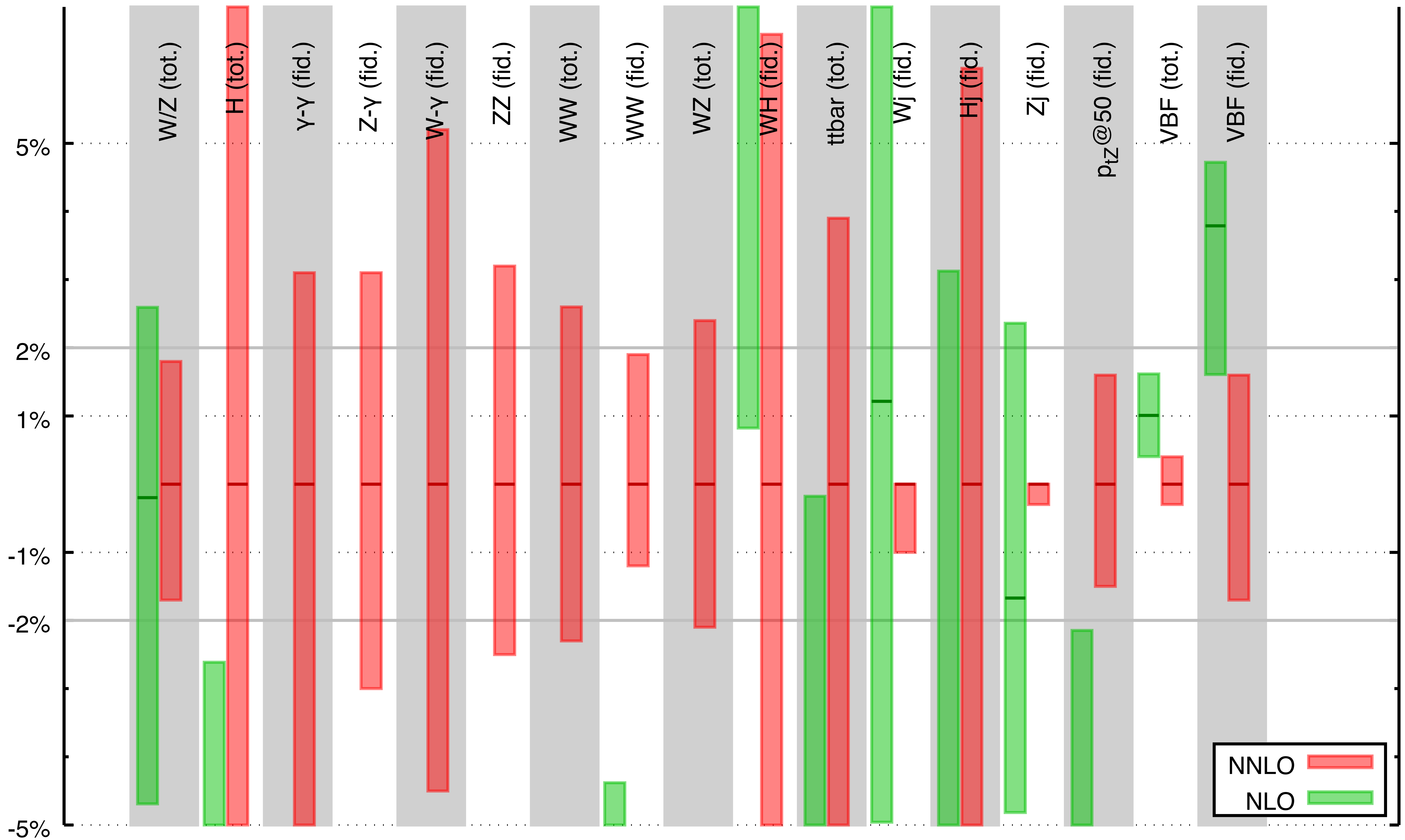
Hard processes: to 3rd order (NNLO) in perturbation theory strong coupling constant (α_s)

as of April 2017

NNLO precision



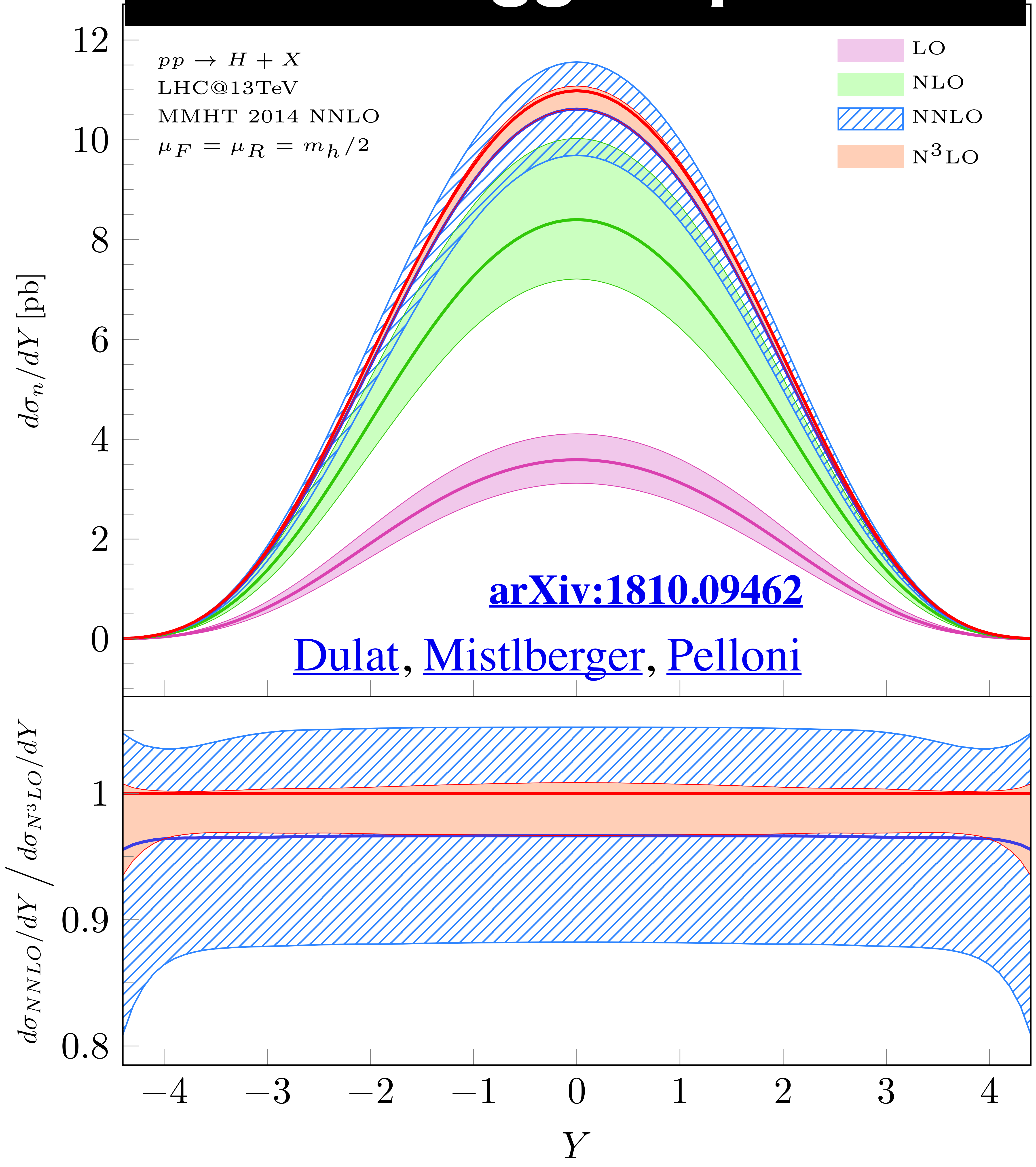
NNLO precision (magnified)



NNLO just barely gets us to 1% accuracy in some cases

(insofar as you believe in uncertainties from scale variation)

N3LO Higgs rap. dist.



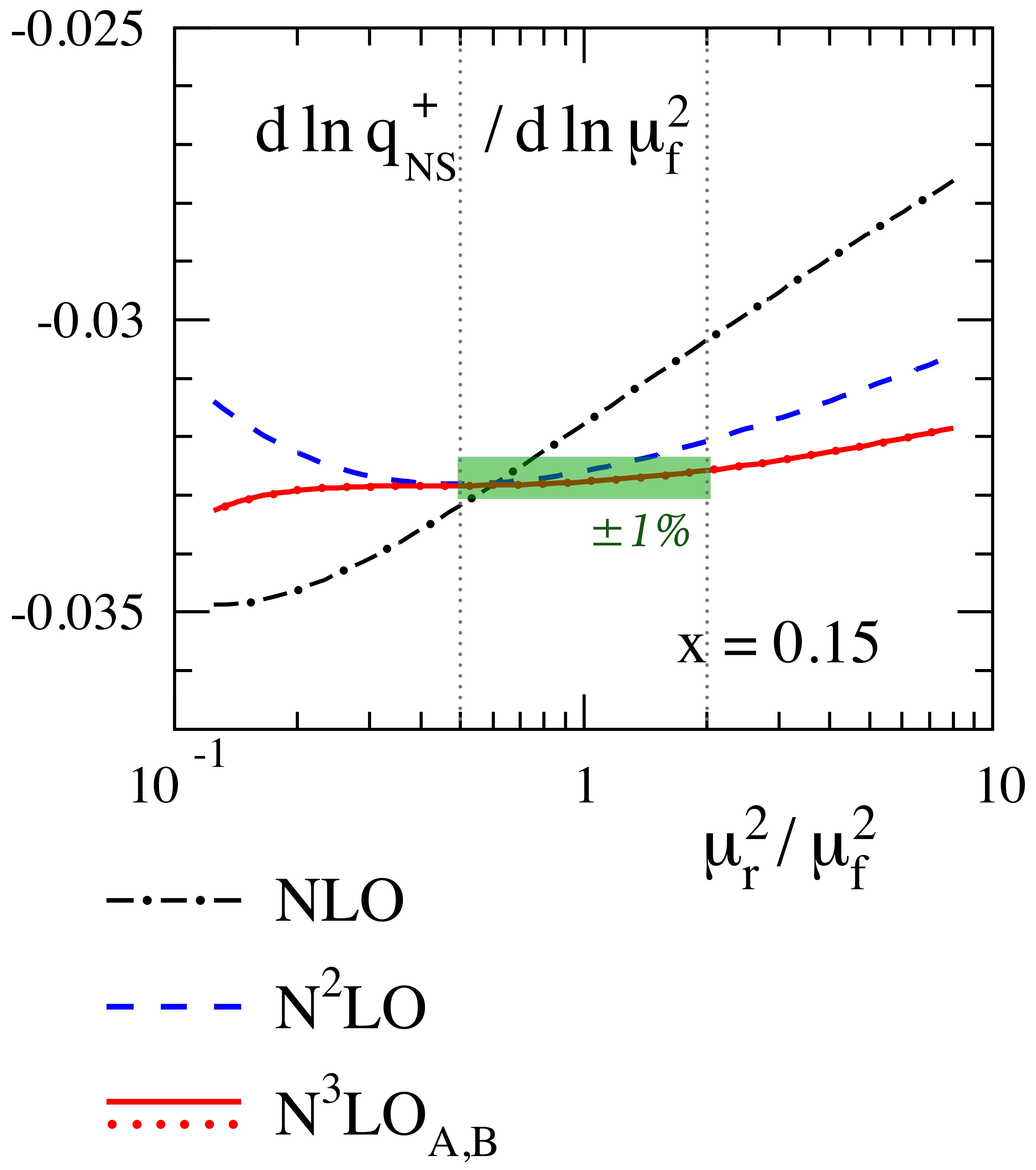
arXiv:1810.09462

Dulat, Mistlberger, Pelloni

NNLO → N3LO

- Technology is there for simple processes
- Demonstrated in Higgs case (poorly convergent perturbative expansion → $^{+0.9\%}_{-3.4\%}$ uncertainty).
- Expect DY/Z production @N3LO soonish, with hope of genuine sub-percent uncertainties.

see also Cieri, Chen, Gehrmann, Glover, Huss arXiv:1807.11501



N3LO splitting functions

- non-singlet splitting functions (e.g. for DGLAP evolution of u-ubar) are now essentially known
- uncertainties on evolution are ~ ±0.5% in the figure (~ half those at NNLO)
- singlet (e.g. P_{gg}) still in progress

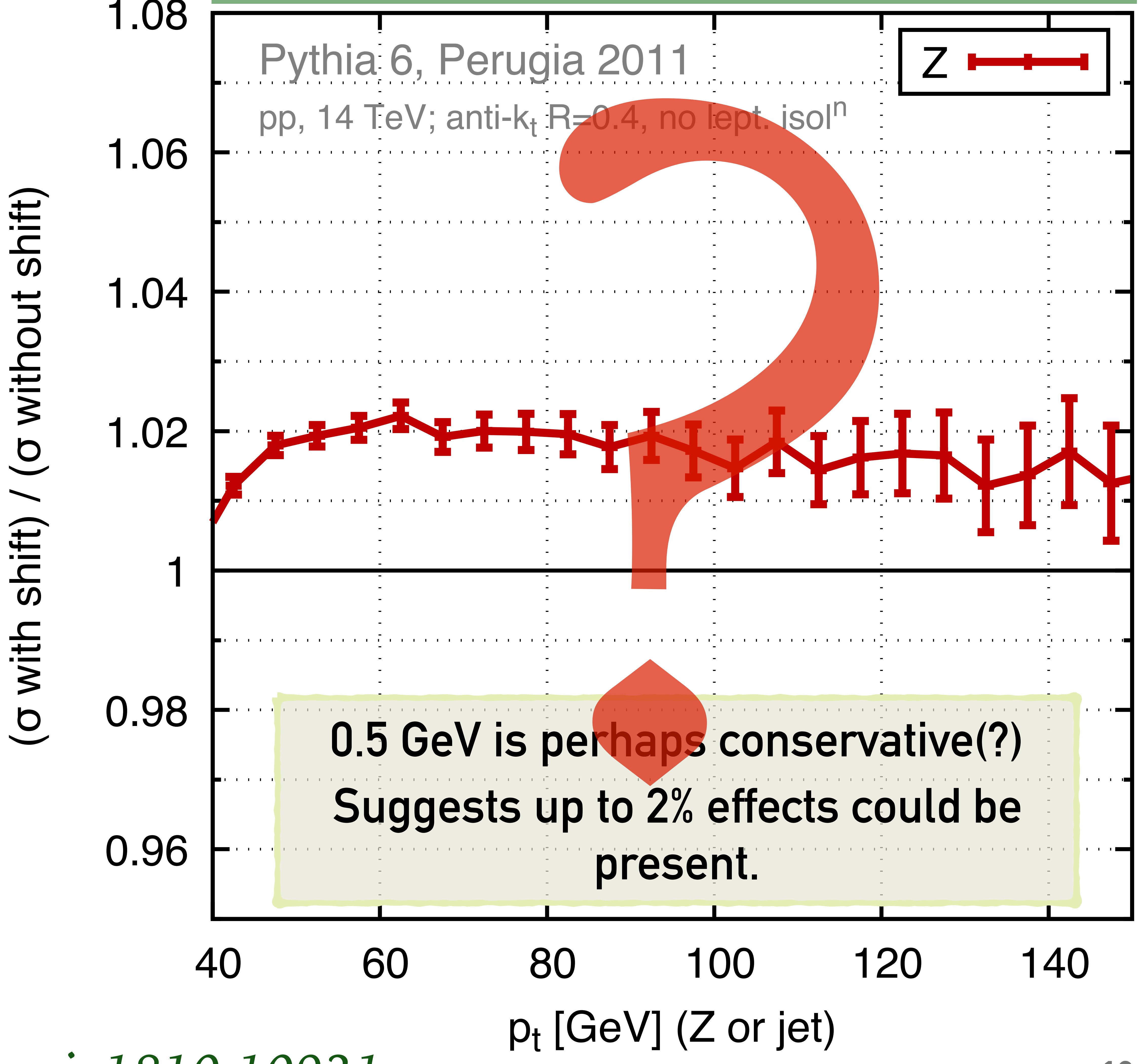
[1707.08315](1707.08315) Moch, Ruijl, Ueda, Vermaseren, Vogt

N4LO progress: 1812.11818

Non-perturbative effects in Z (& H?) p_T

- **Inclusive** Z/W, H,VV cross sections should have $\sim\Lambda_{QCD}^2/M^2$ **corrections** **($\sim 10^{-4}$?)**
- Z (&H) p_T **not inclusive** so corrections can be $\sim\Lambda/M$.
- Size of effect can't be probed by turning MC hadronisation on/off [maybe by modifying underlying MC parameters?]
- Shifting Z p_T by a finite amount illustrates what could happen

impact of 0.5 GeV shift of Z p_T



Techniques to answer this: Ferrario-Ravasio, Jezo, Nason & Oleari, 1810.10931

what might we do with it?

0. many processes, much phase space within 1% statistical reach

A huge range of phasespace will reach < 1% statistical precision @ HL-LHC

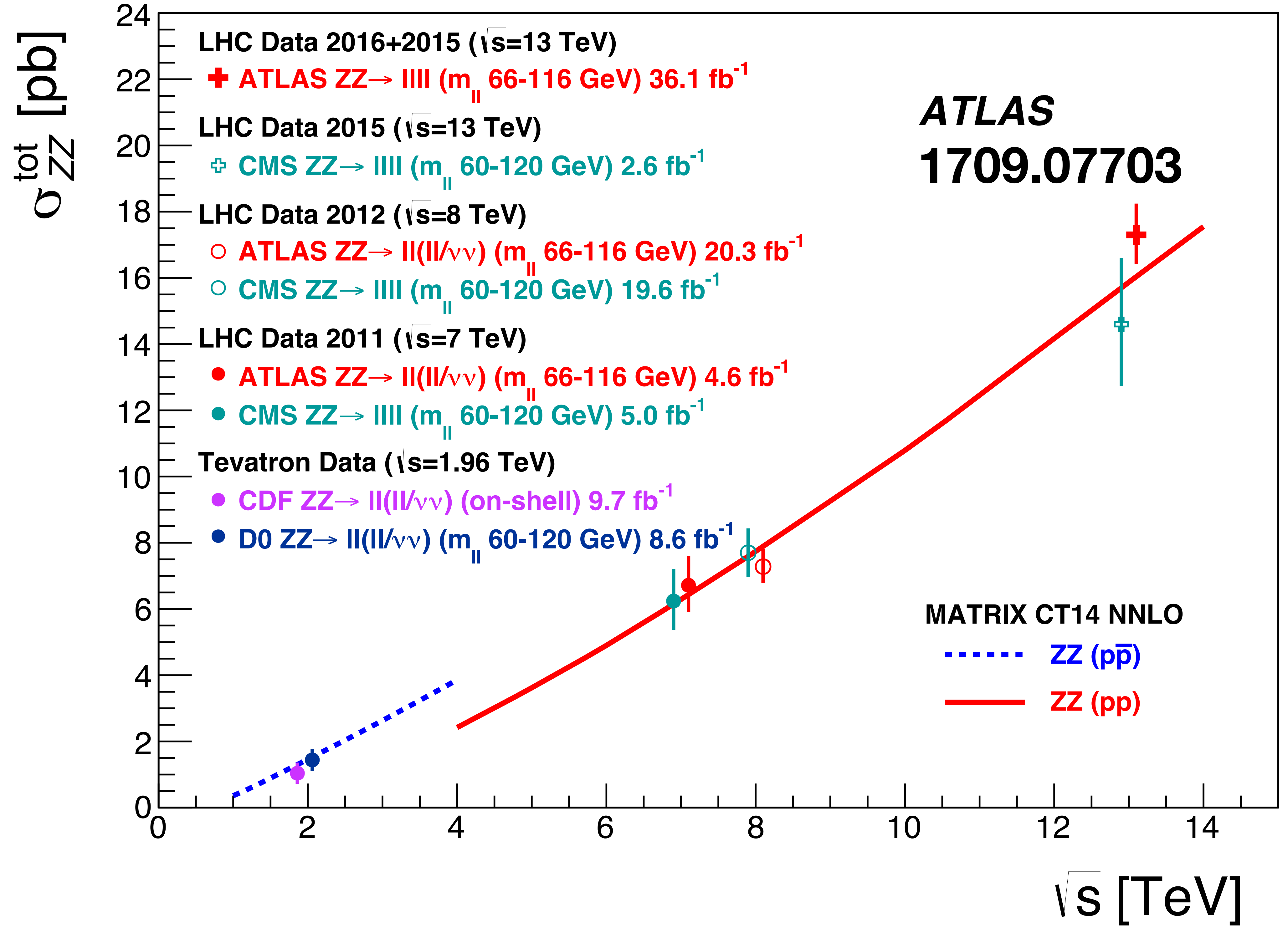
For example, processes with two or more leptons

- Drell-Yan: $m_{\mu\mu}$ up to 1 TeV
- high pT Z, up to 1 TeV
- top-antitop (di-lepton channels)
  - Mtt up to 2 TeV,
  - $p_{T,top}$ up to 1 TeV
- VV production

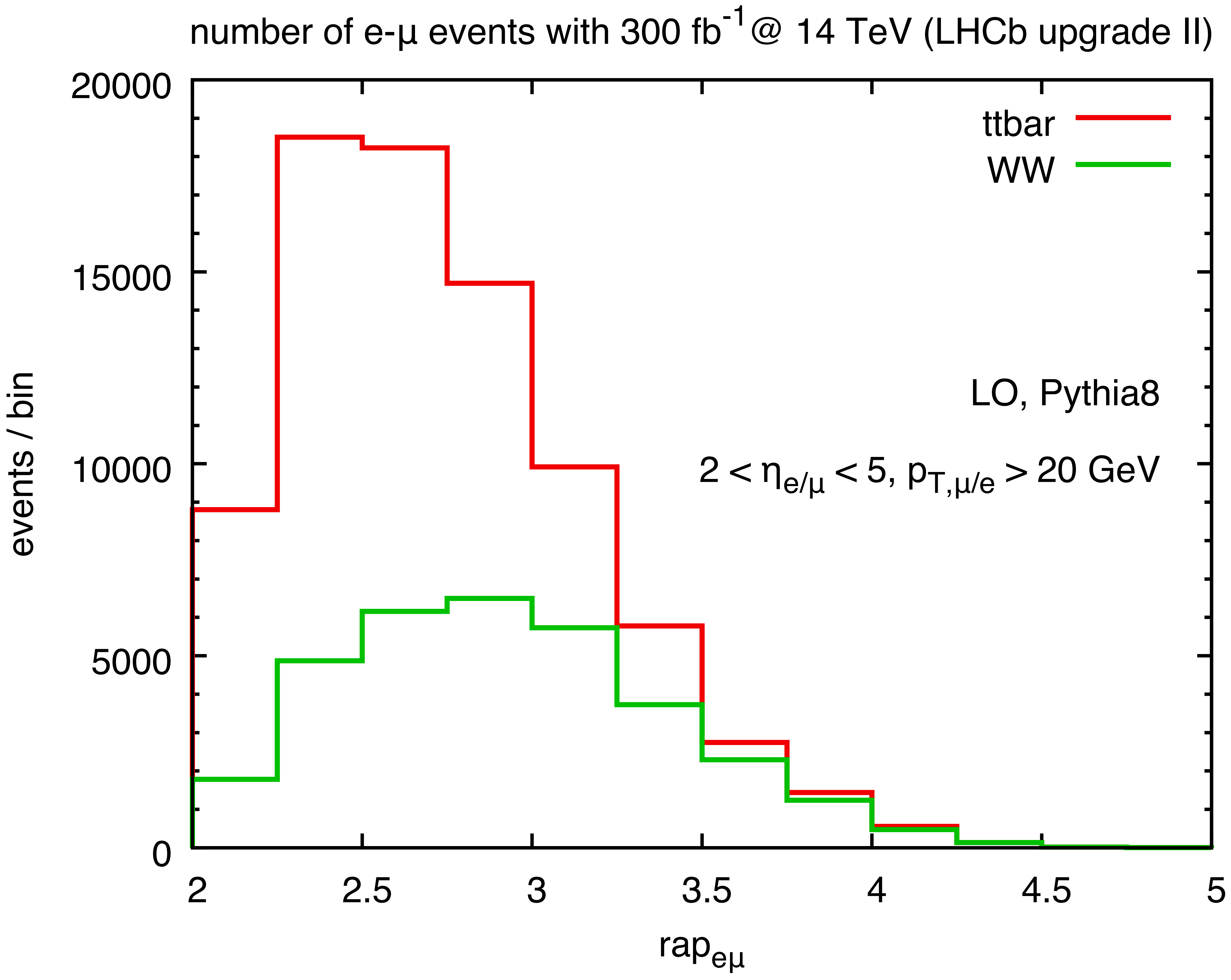
ZZ

36.1fb^{-1} @ 13 TeV:
17.3 ± 0.9 [±0.6 (stat.) ±0.5 (syst.) ±0.6 (lumi.)] pb.

→ expect stat errs of 0.3% for 3000 fb^{-1}



e–μ events (a mix of ttbar and VV) at LHCb



this is a quick study to gauge orders of magnitude (Pythia8, LO, no showering)

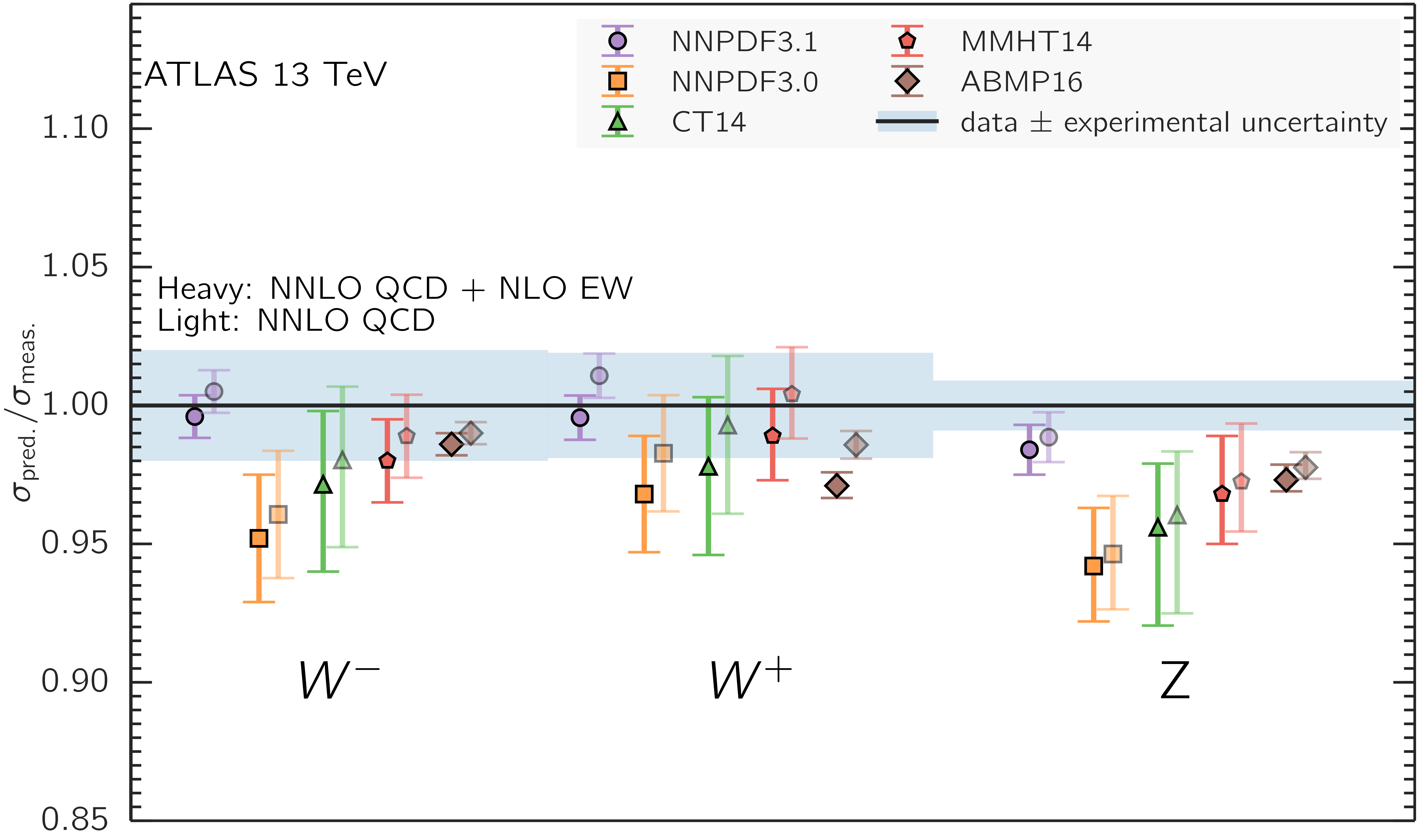
N(N)LO K-factors will increase rates significantly

there will also be other VV channels (probably smaller)

what might we do with it?

1. As an input to everything else: PDFs

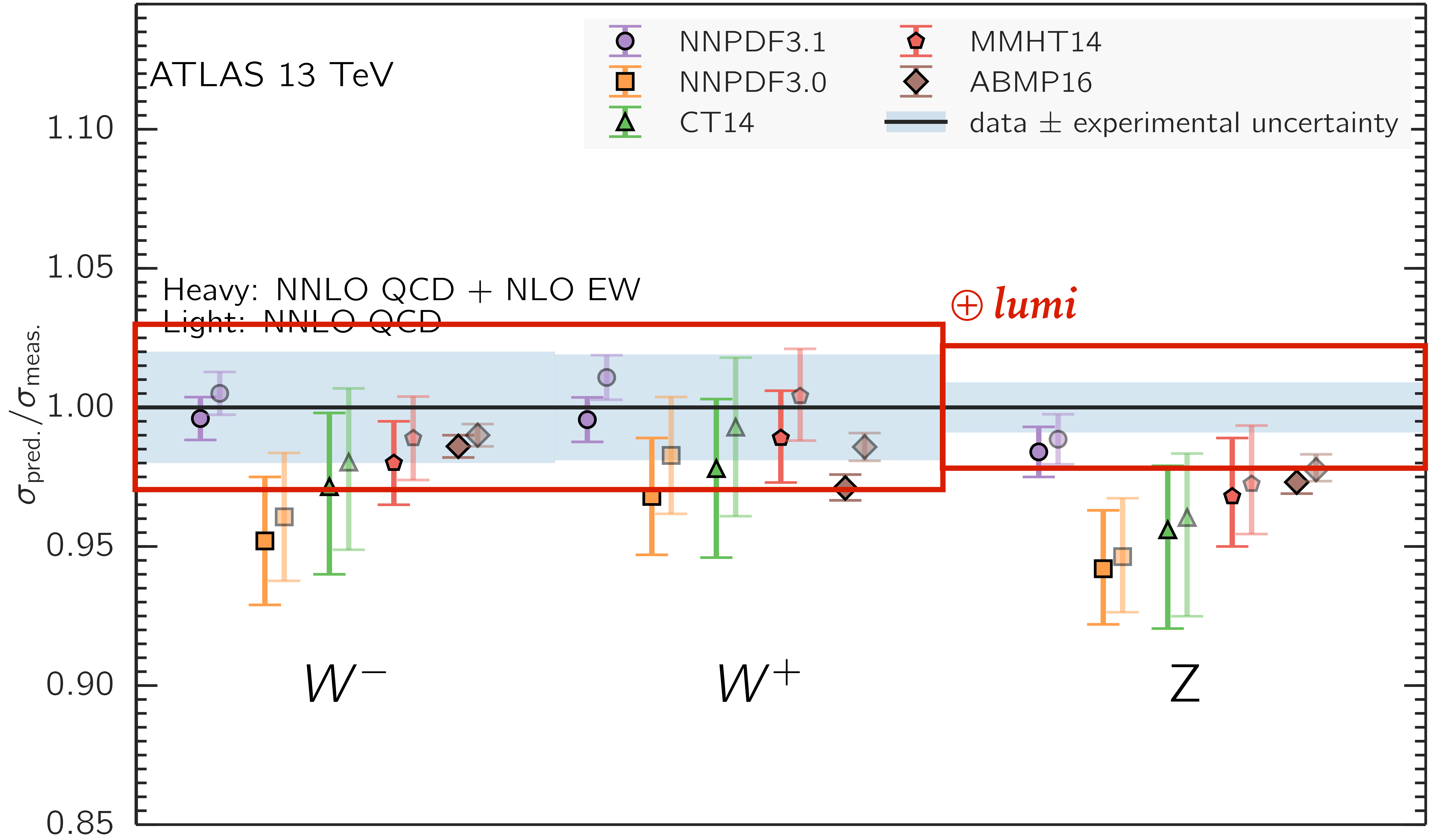
Drell–Yan as input to PDF fits



NNPDF3.1, 1706.00428 (data from 1603.09222)

PDFs in the most basic process, Drell–Yan/Z, would be tightly constrained (~0.9%) were it not for the luminosity uncertainty (~2%)

Drell–Yan as input to PDF fits



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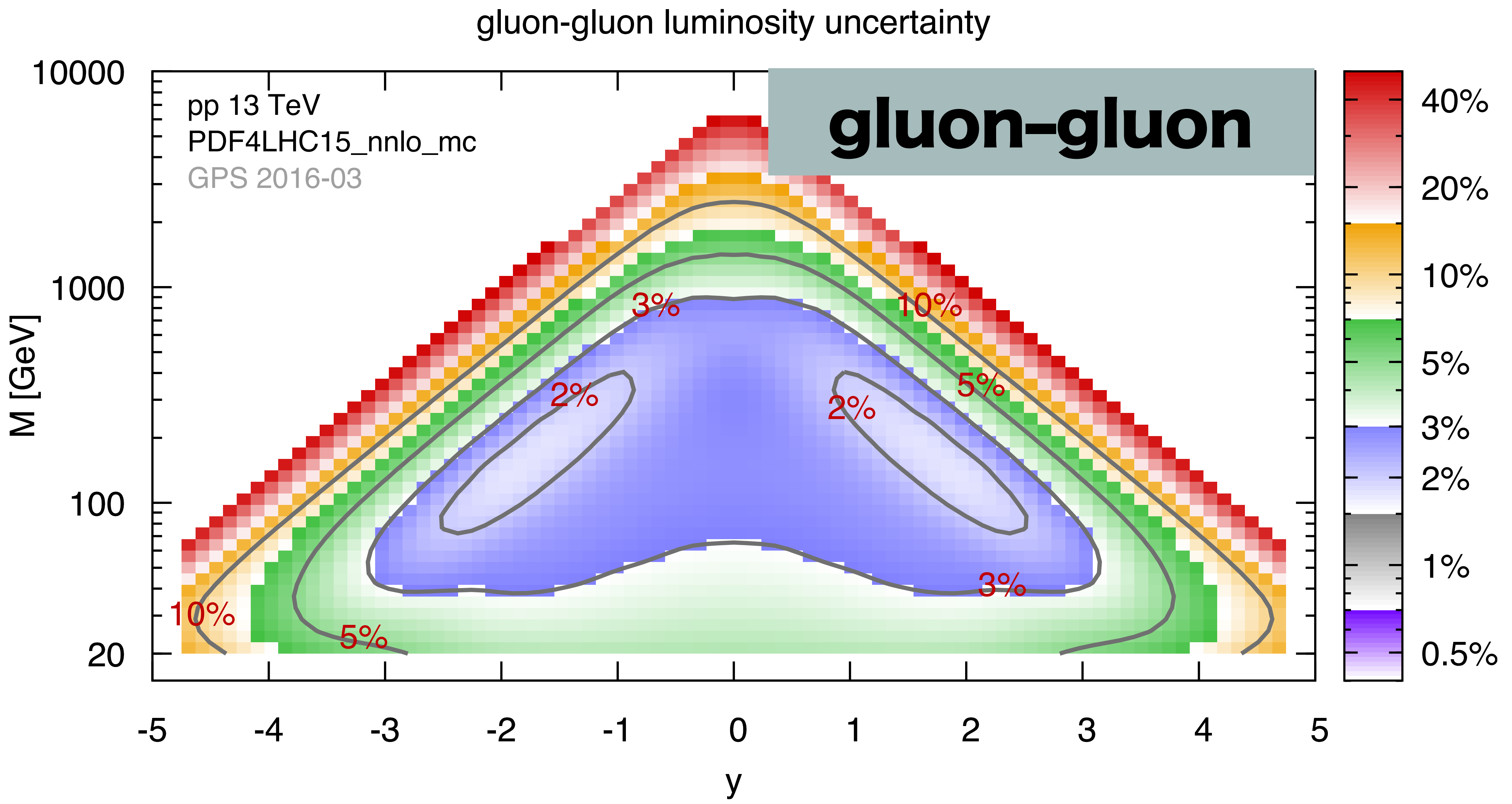
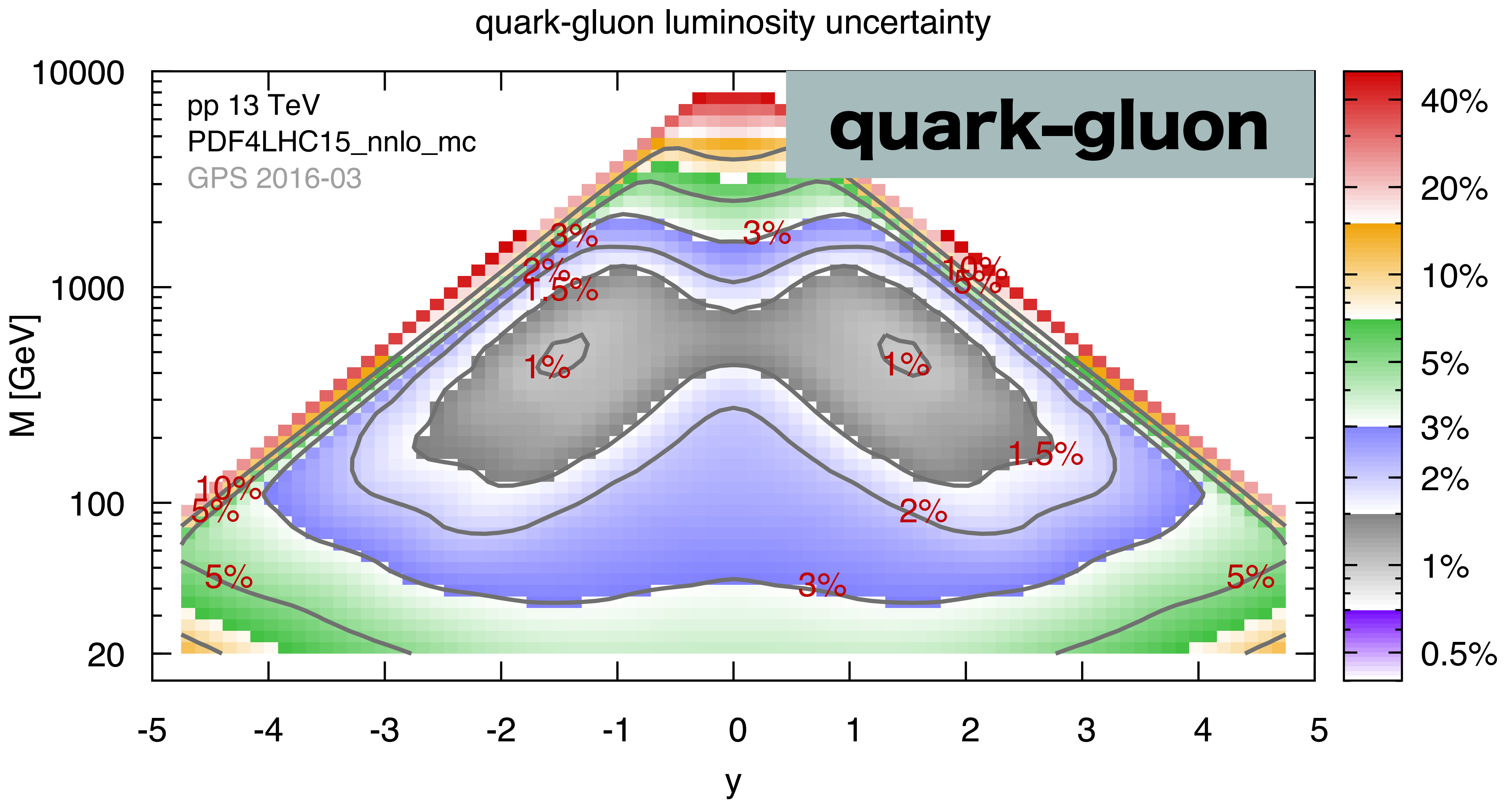
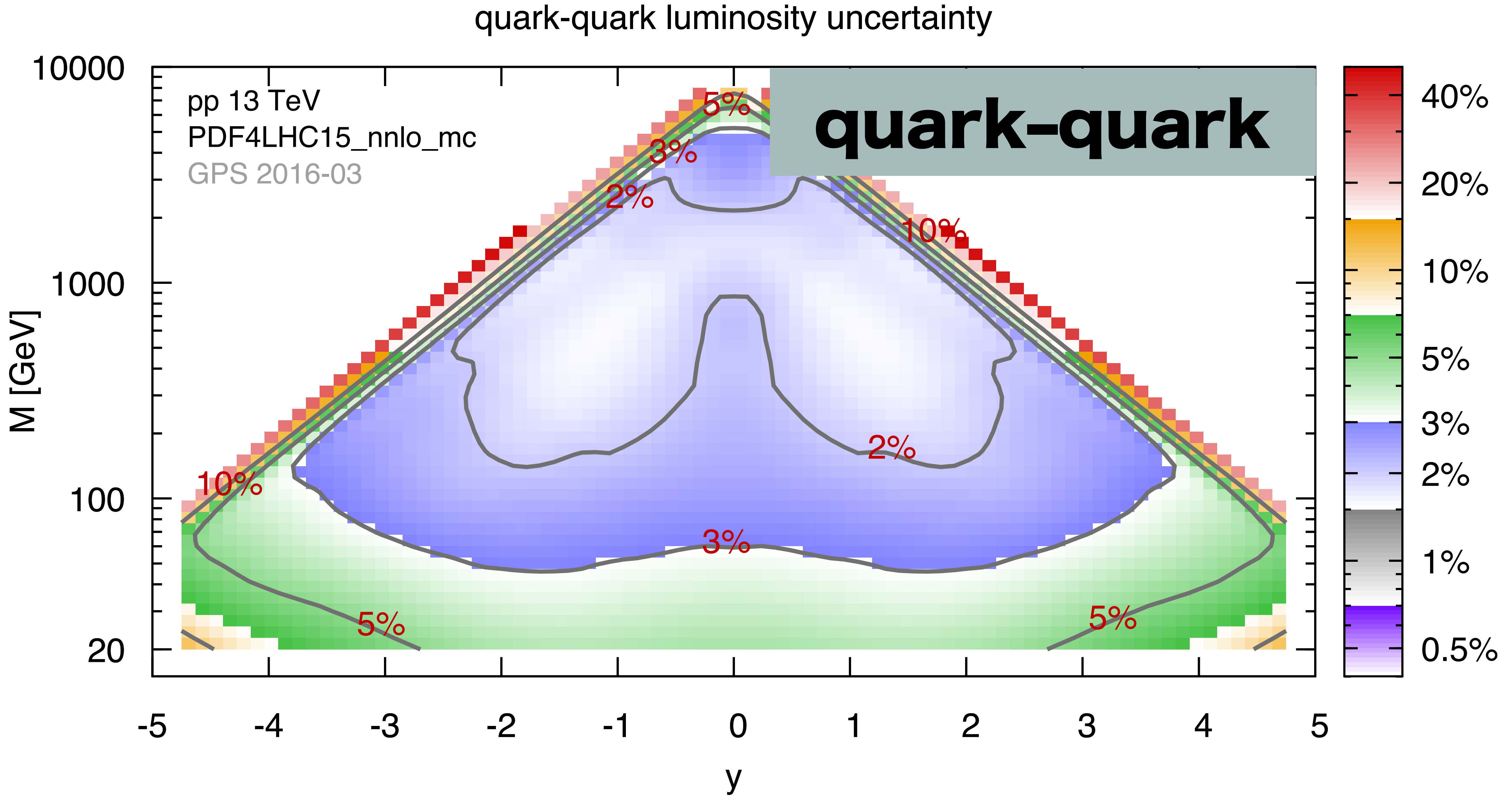
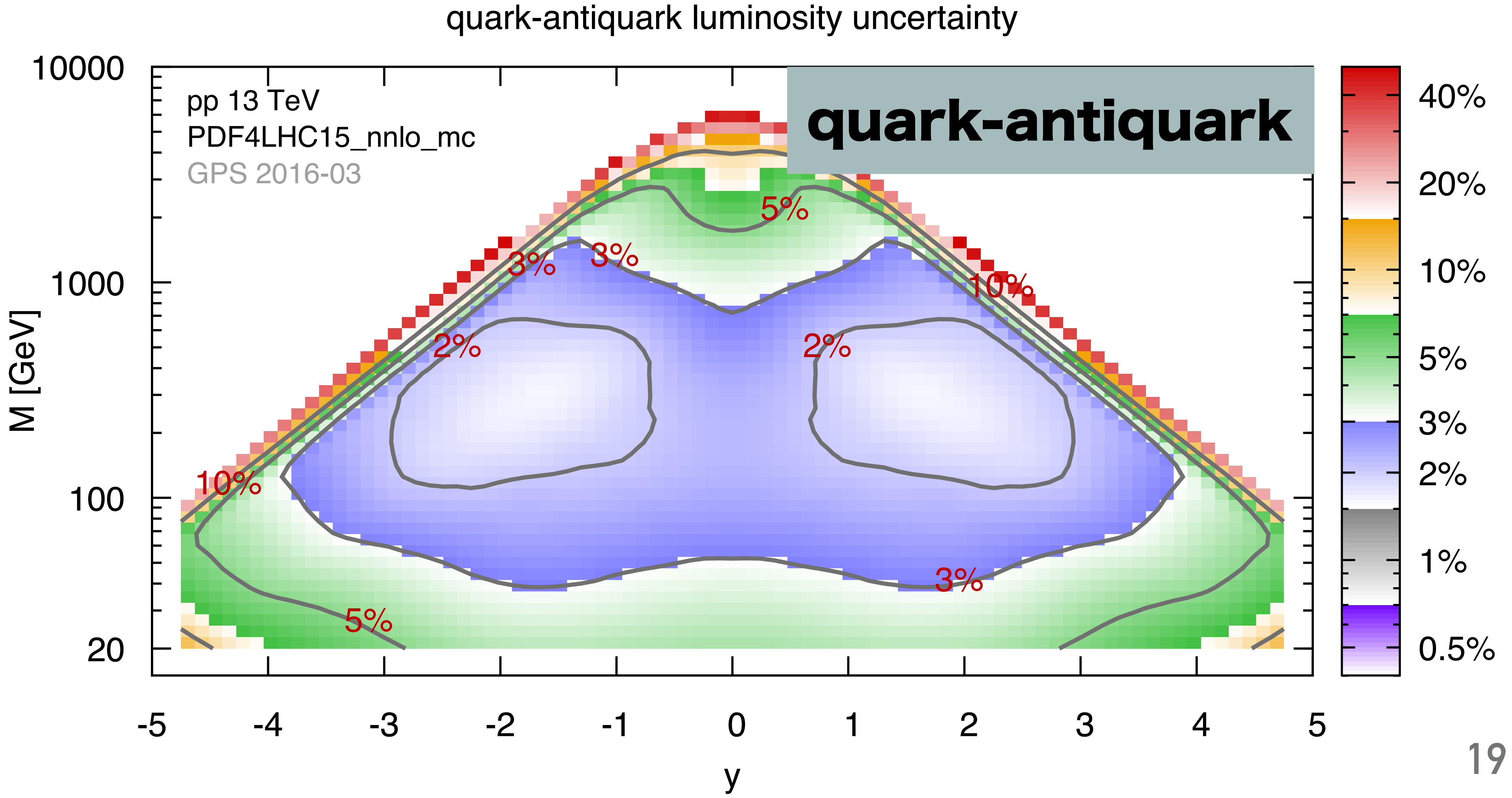
Uncertainties on partonic luminosities — v. rapidity(y) and mass





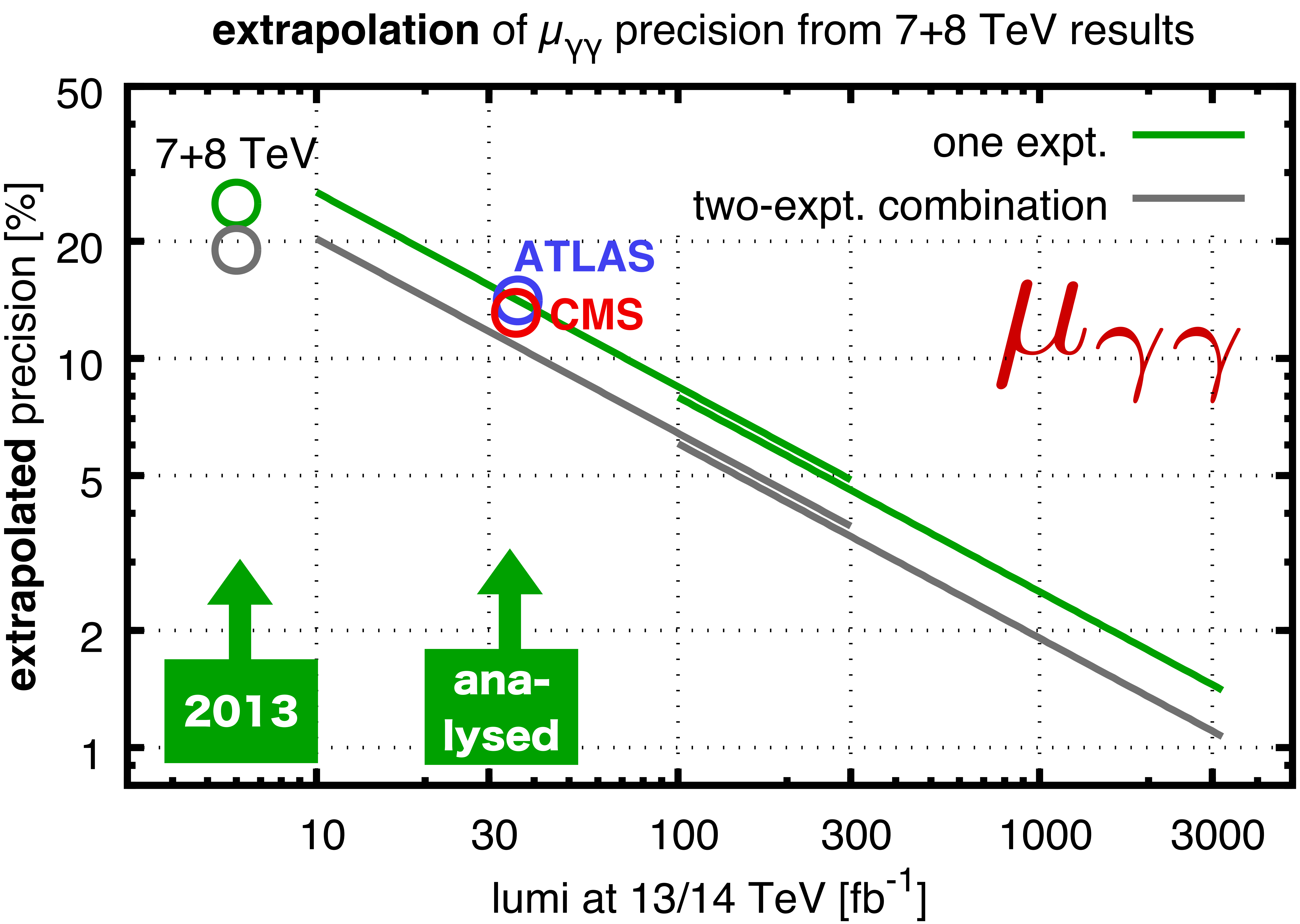




what might we do with it?

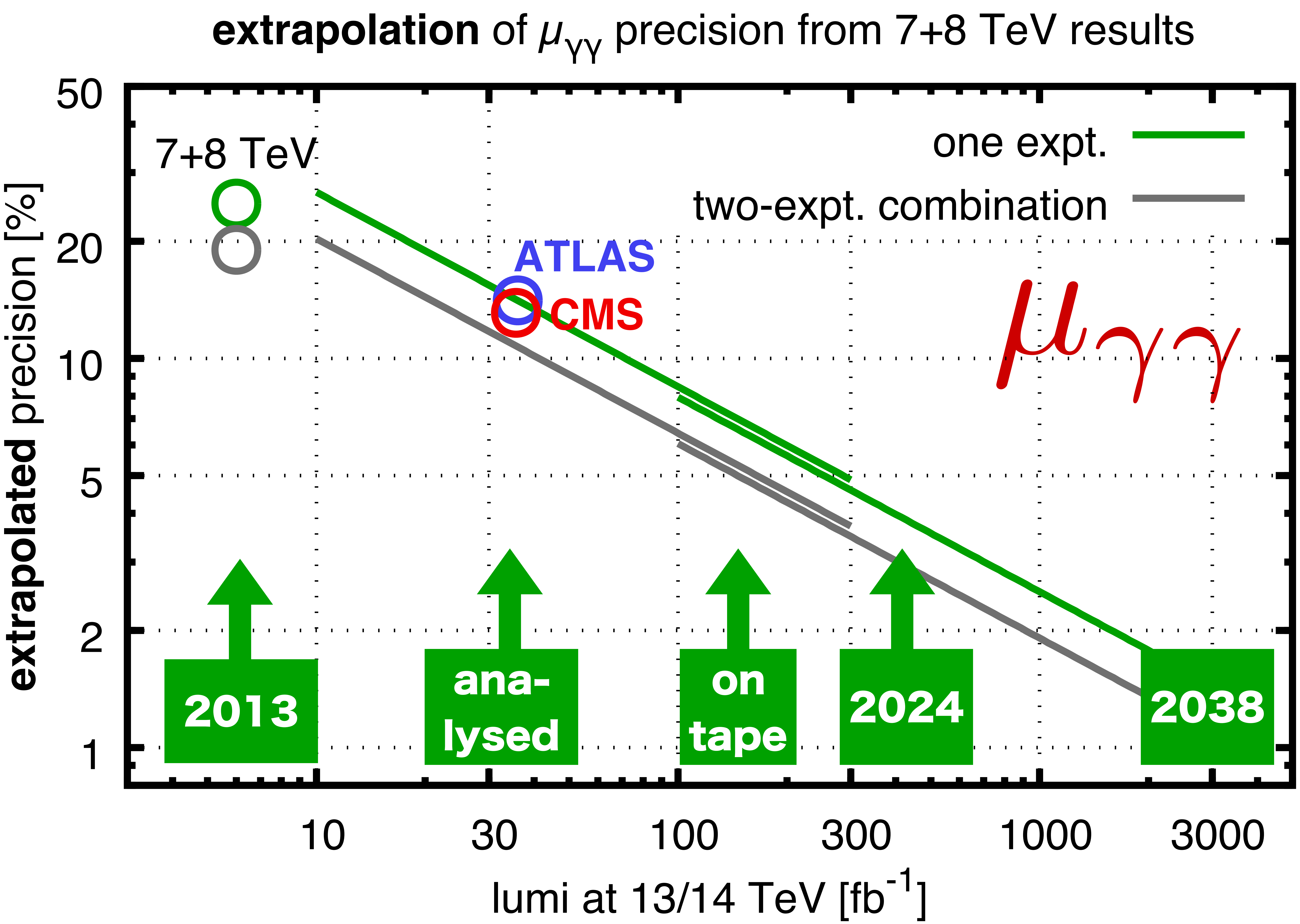
2. Higgs

Higgs precision (H → γγ) : semi-optimistic estimate v. luminosity & time



1 fb^{-1} = 10^{14} collisions

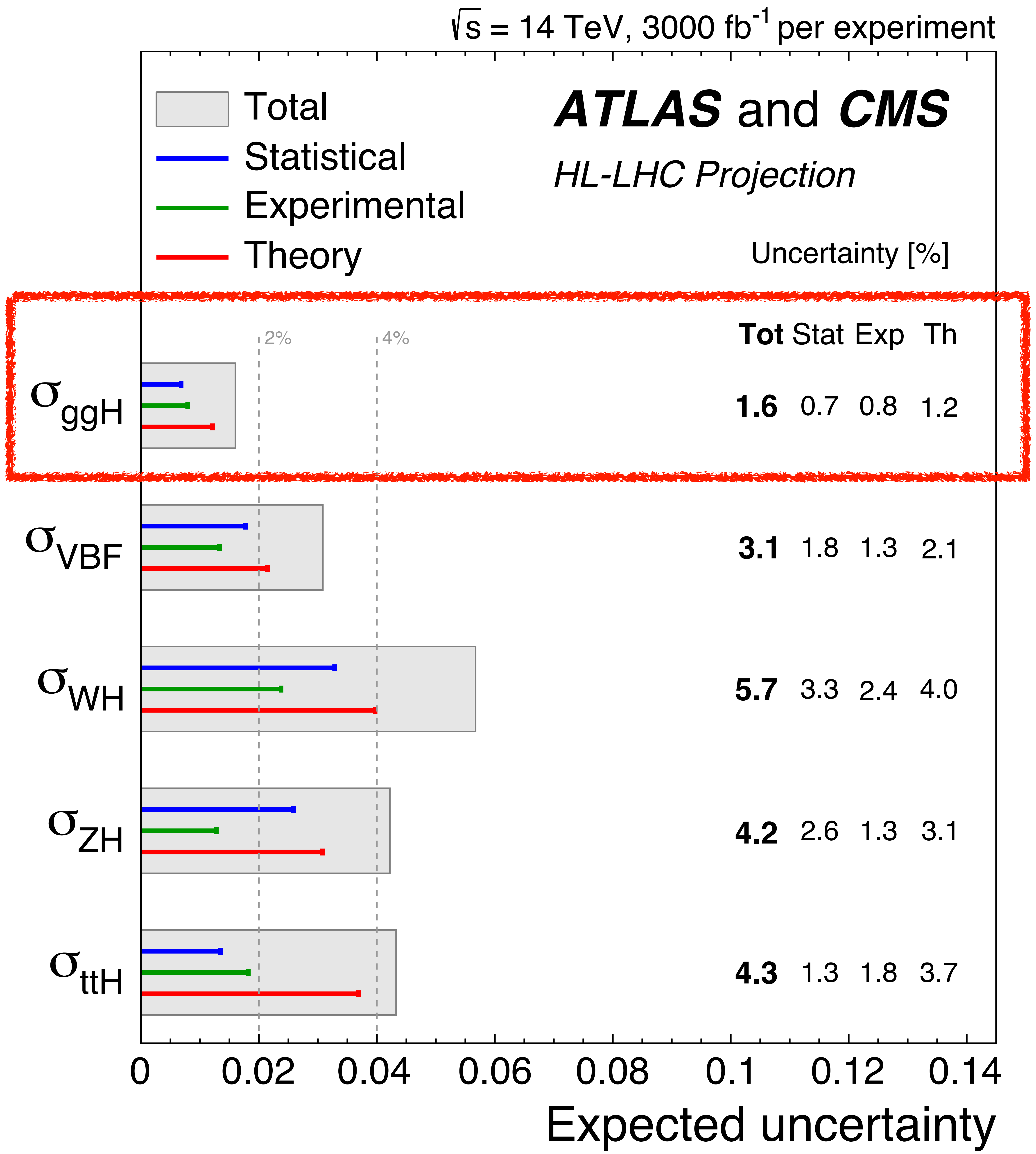
Higgs precision (H → γγ) : semi-optimistic estimate v. luminosity & time



The LHC has the statistical potential to take Higgs physics from "observation" to 1–2% precision

But only if we learn how to connect experimental observations with theory at that precision

1 fb^{-1} = 10^{14} collisions



CERN-LPCC-2018-04
December 21, 2018

Higgs Physics
at the HL-LHC and HE-LHC

Official Higgs projections for HL-LHC indicate 1% experimental uncertainties from ATLAS/CMS combination for main production cross section, σ_{ggH}

Credibility will be greatly enhanced if we can demonstrate <1% control across a range of processes

DI-HIGGS PRODUCTION AT HL-LHC ($HH \to 4b$, $3ab^{-1}$)

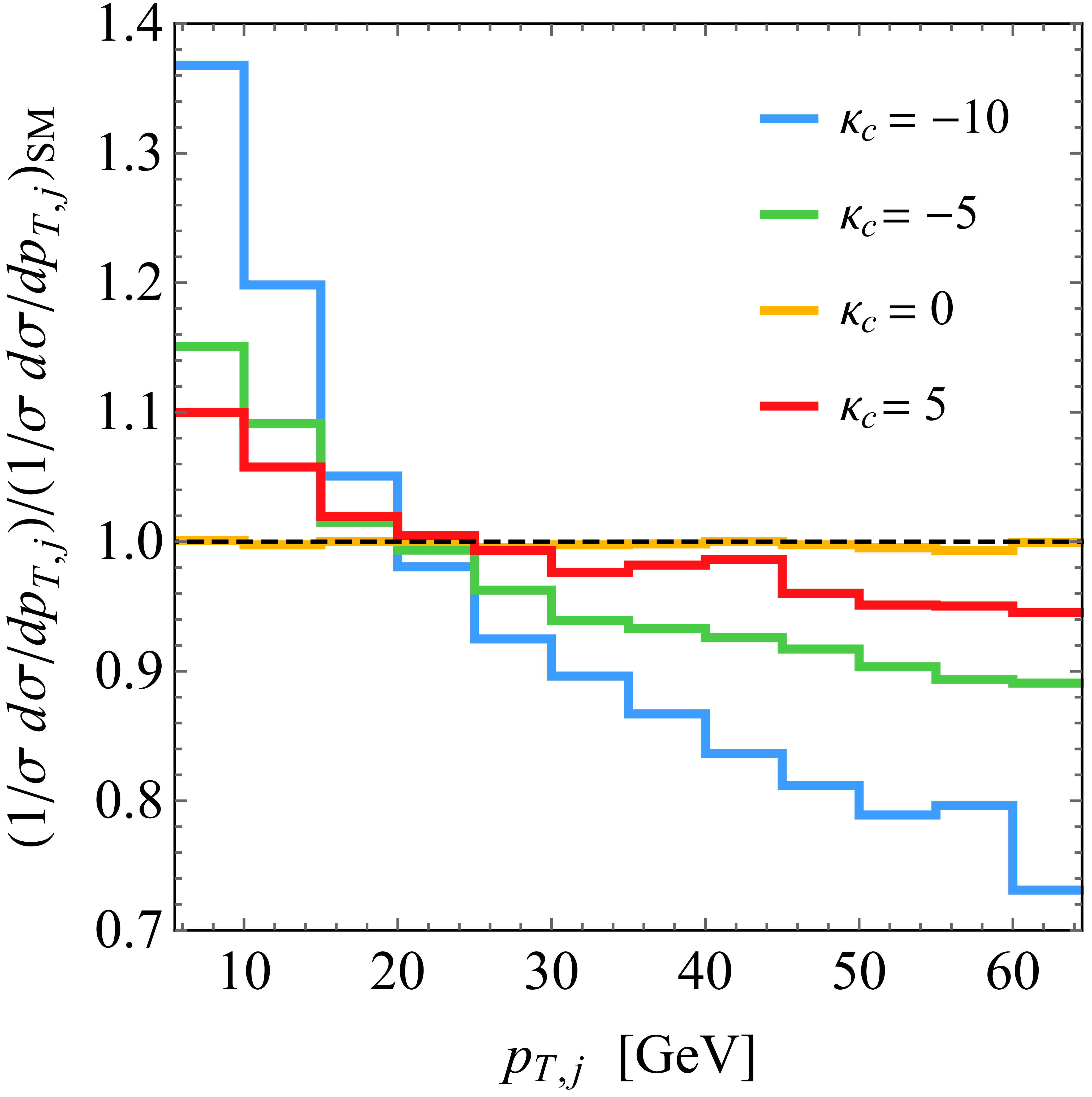
Behr, Bortoletto, Frost, Hartland, Issever & Rojo, 1512.08928

Category		signal N_{ev}	background N_{ev}^{tot}	background N_{ev}^{4b}	$S/\sqrt{B_{tot}}$	$S/\sqrt{B_{4b}}$	S/B_{tot}	S/B_{4b}
Boosted	no PU	290	$1.2 \cdot 10^4$	$8.0 \cdot 10^3$	2.7	3.2	0.03	0.04
	PU80+SK+Trim	290	$3.7 \cdot 10^4$	$1.2 \cdot 10^4$	1.5	2.7	0.01	0.02
Intermediate	no PU	130	$3.1 \cdot 10^3$	$1.5 \cdot 10^3$	2.3	3.3	0.04	0.08
	PU80+SK+Trim	140	$5.6 \cdot 10^3$	$2.4 \cdot 10^3$	1.9	2.9	0.03	0.06
Resolved	no PU	630	$1.1 \cdot 10^5$	$5.8 \cdot 10^4$	1.9	2.7	0.01	0.01
	PU80+SK	640	$1.0 \cdot 10^5$	$7.0 \cdot 10^4$	2.0	2.6	0.01	0.01
Combined	no PU				4.0	5.3		
	PU80+SK+Trim				3.1	4.7		

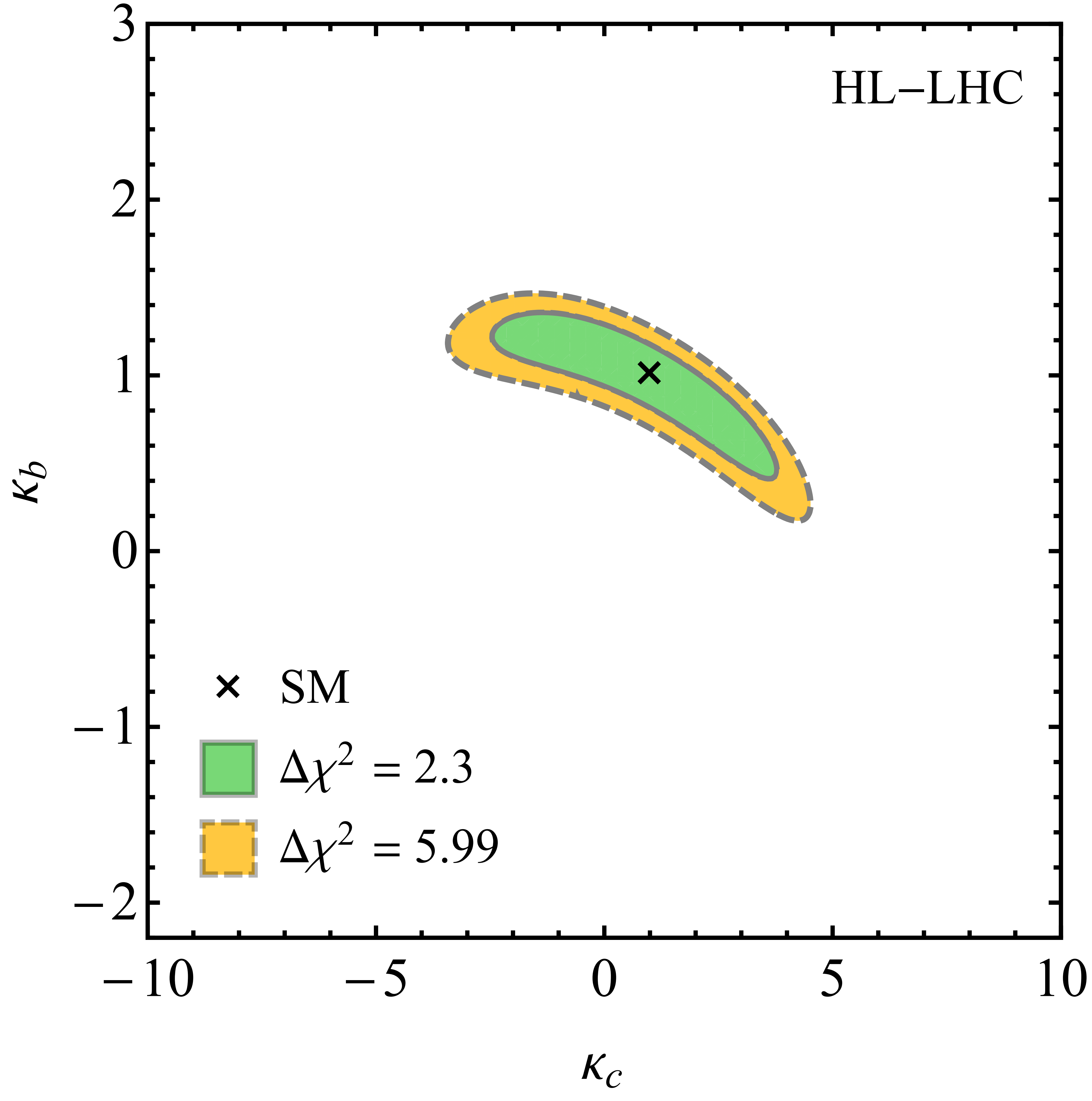
Key signal channels will need ~1% control of complex bkgds

indirect constraints on Hcc

impact of modified Hcc coupling on Higgs+jet p_T dist



joint limits on κ_c & κ_b @ HL-LHC



Fady Bishara, Ulrich Haisch, Pier Francesco Monni and Emanuele Re, arXiv:1606.09253

what might we do with it?

3. New physics searches

VH production at large m(VH) [specific illustration of a generic point]

See also e.g. Biekötter, Knochel, Krämer, Liu, Riva, arXiv:1406.7320

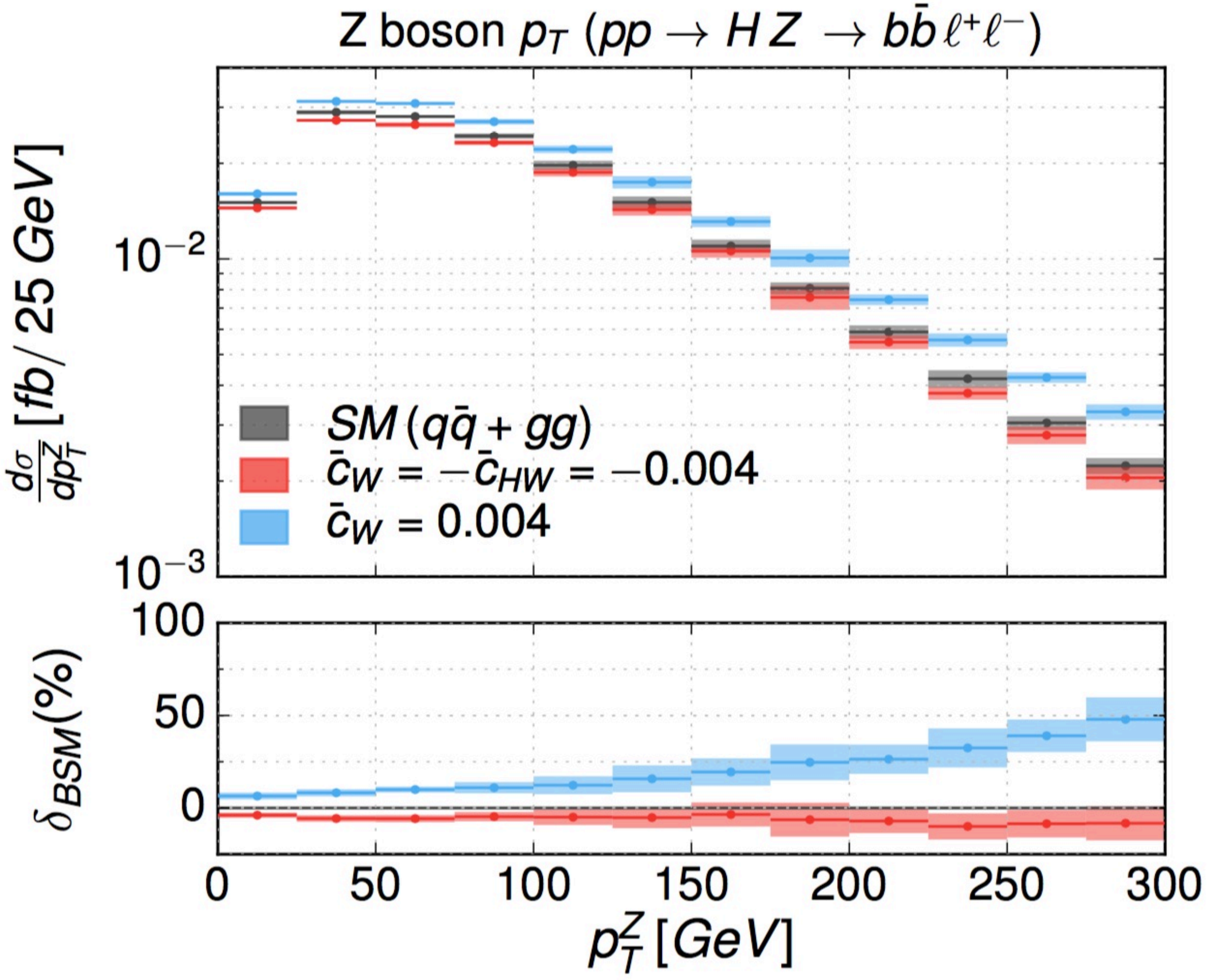
- Higher-dimension operators cause deviations that grow as, e.g.

$$\frac{\delta\sigma_{\text{dim-6}}}{\sigma} \sim \frac{p_T^2}{\Lambda^2}$$

- In some relevant range of p_T, Λ value to which you're sensitive grows as

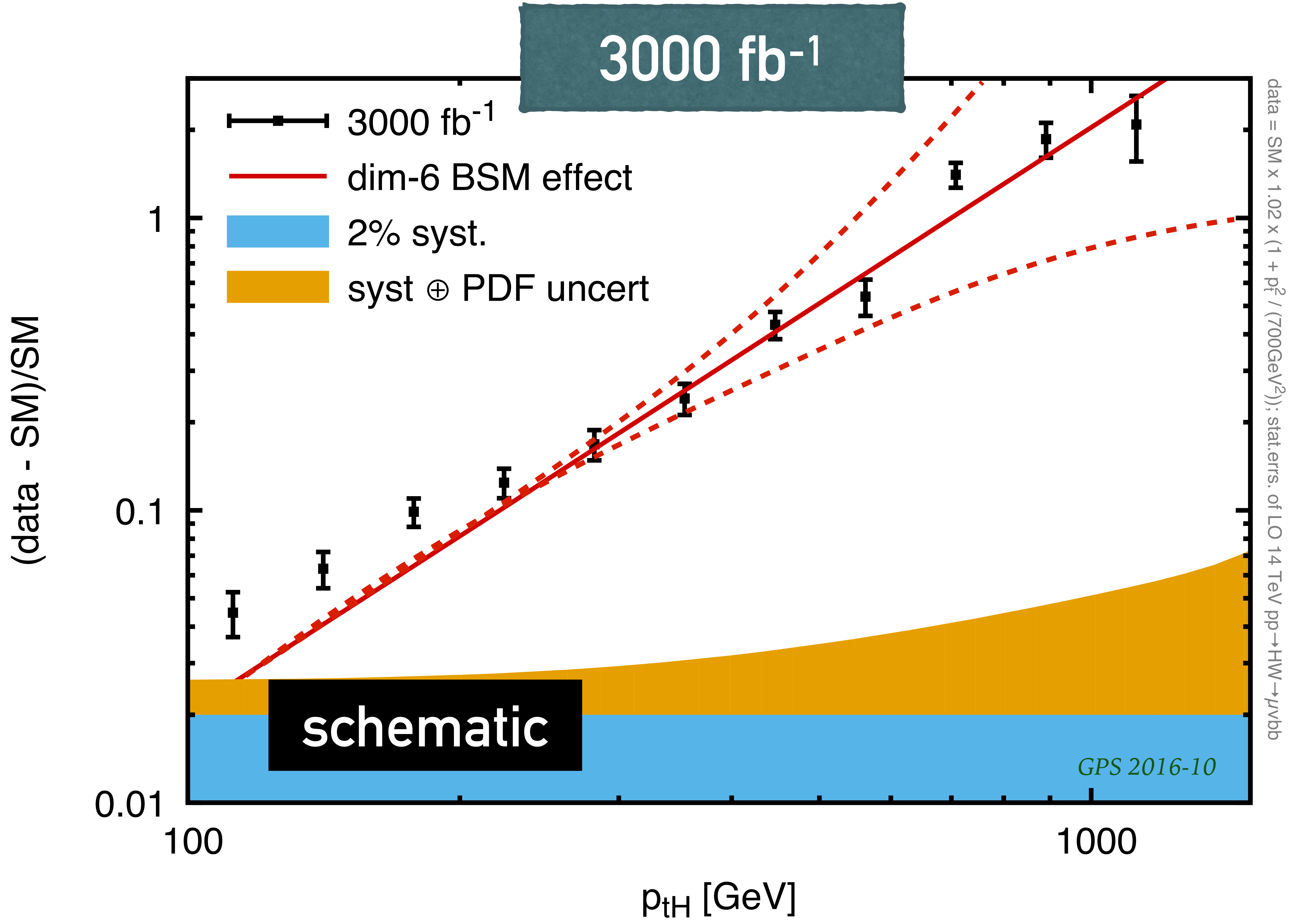
$$\Lambda \sim (\text{Lumi})^{1/4}$$

- that's faster than most direct searches (x100 in lumi → x1.5 in reach for Z')



Mimasu, Sanz, Williams, arXiv:1512.02572v

WH at large Q^2 with dim-6 BSM effect

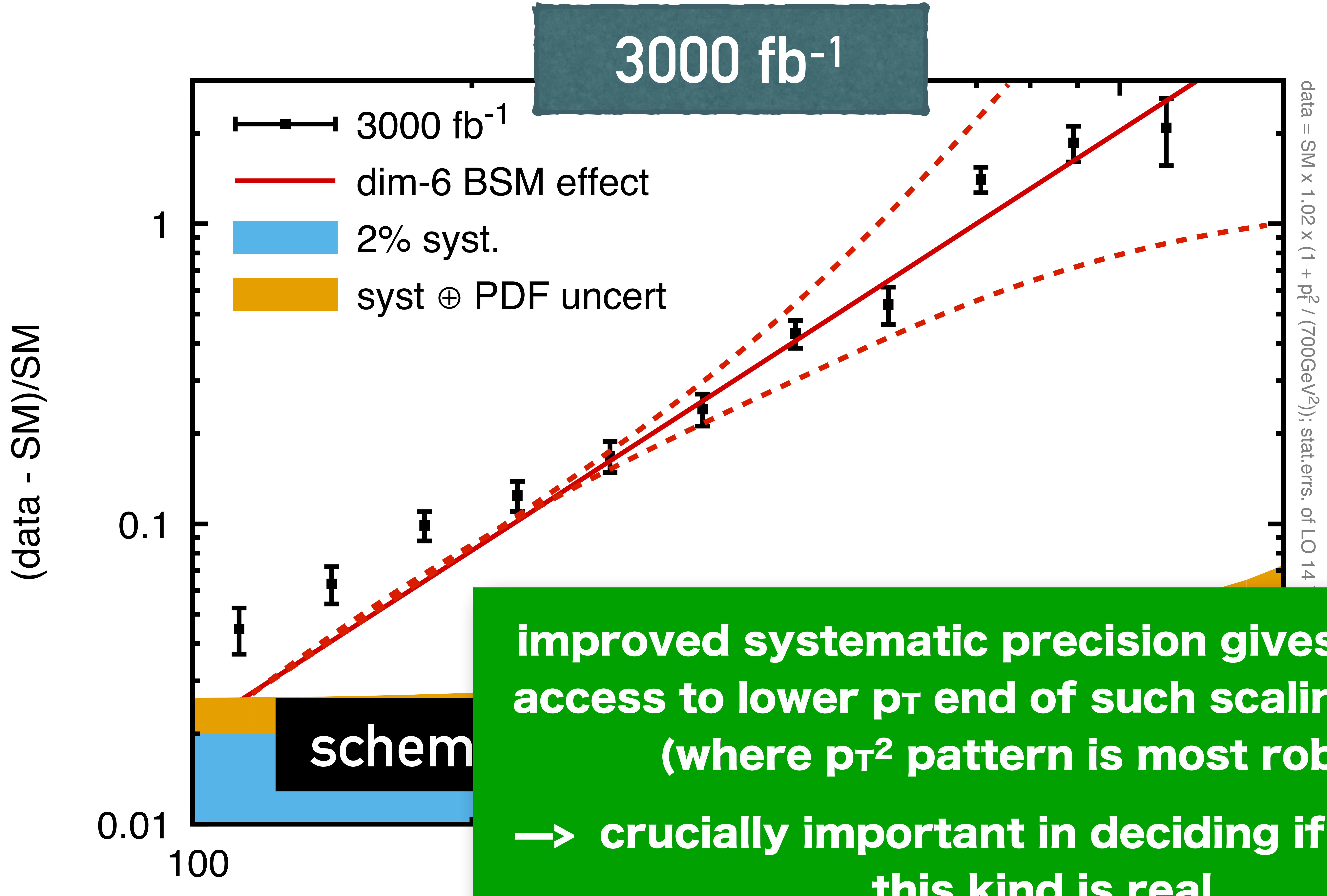


new physics isn't just a single number that's wrong (think g-2)

but rather a distinct scaling pattern of deviation ($\sim p_T^2$)

moderate and high p_T's have similar statistical significance — so it's useful to understand whole p_T range

WH at large Q^2 with dim-6 BSM effect



improved systematic precision gives enhanced access to lower p_T end of such scaling patterns (where p_T^2 pattern is most robust)

⟶ crucially important in deciding if a signal of this kind is real

new physics isn't just a single number that's wrong (think g-2)

but rather a distinct scaling pattern of deviation (~ p_T^2)

moderate and high p_T's … ilar statistical … nce — so it's … o understand … e p_T range

conclusions

Conclusions

- **Experimentally:** relative sub-percent precision looks feasible for many leptonic processes. Open question is absolute precision, especially luminosity.
- **Theoretically:** expect substantial further progress on higher-order perturbative calculations. For a subset of processes (non-inclusive), open questions about non-perturbative effects. *[Technology probably exists to answer this questions]*
- **Varied applications:**
  - many processes, over wide phasespace, will have statistical precision $< 1\%$
  - could bring PDFs into new era of precision (& complementary to low-Q^2 DIS?)
  - will build confidence in precision needed for precision Higgs physics
  - can provide crucial low-p_T end of lever-arm in searches for higher-dim. BSM operators

backup

Input parameters? Especially, α_s

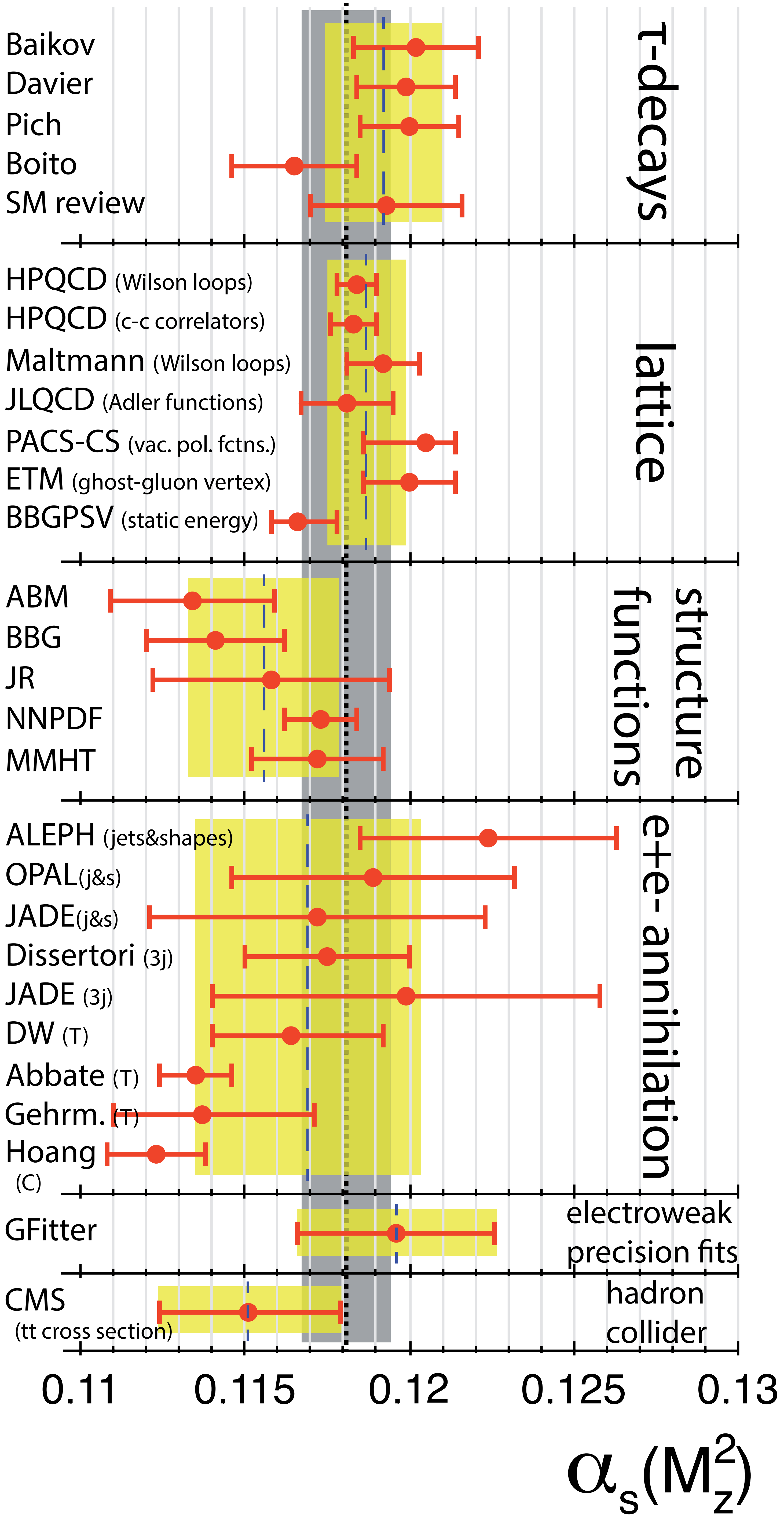
(almost) all theory predictions for LHC are based on perturbation theory, e.g.

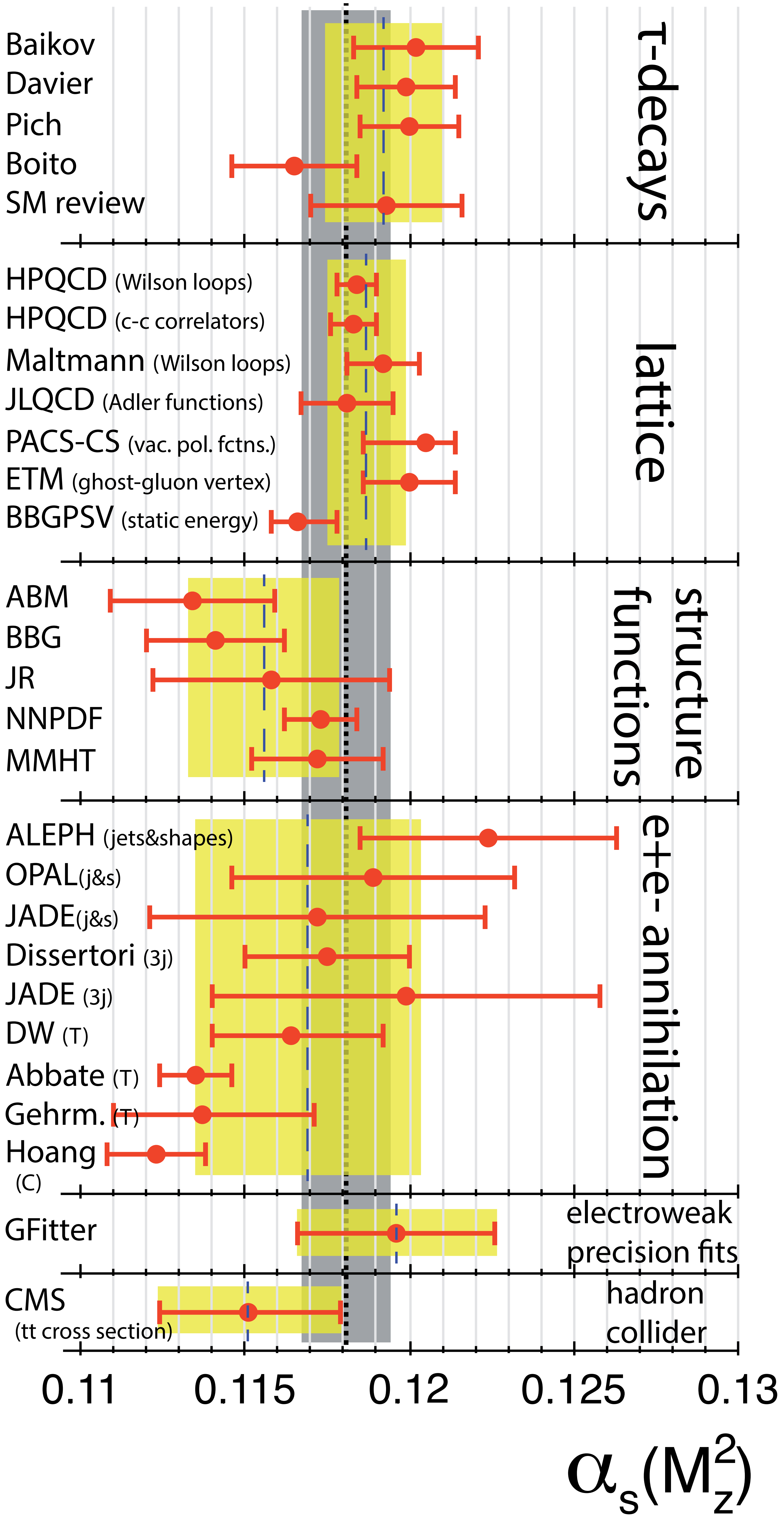
$$\sigma = a_s\sigma_1 + a_s^2\sigma_2 + \ldots$$

not so critical for DY, VV (LO doesn't depend on a_s), but is crucial for ttbar and other processes that start at $O(a_s^2)$

PDG World Average: $\alpha_s(M_Z) = 0.1181 \pm 0.0013$ (1.1%)

Bethke, Dissertori & GPS in PDG '16





PDG World Average: $\alpha_s(M_Z) = 0.1181 \pm 0.0013$ (1.1%)

➤ Most consistent set of independent determinations is from lattice

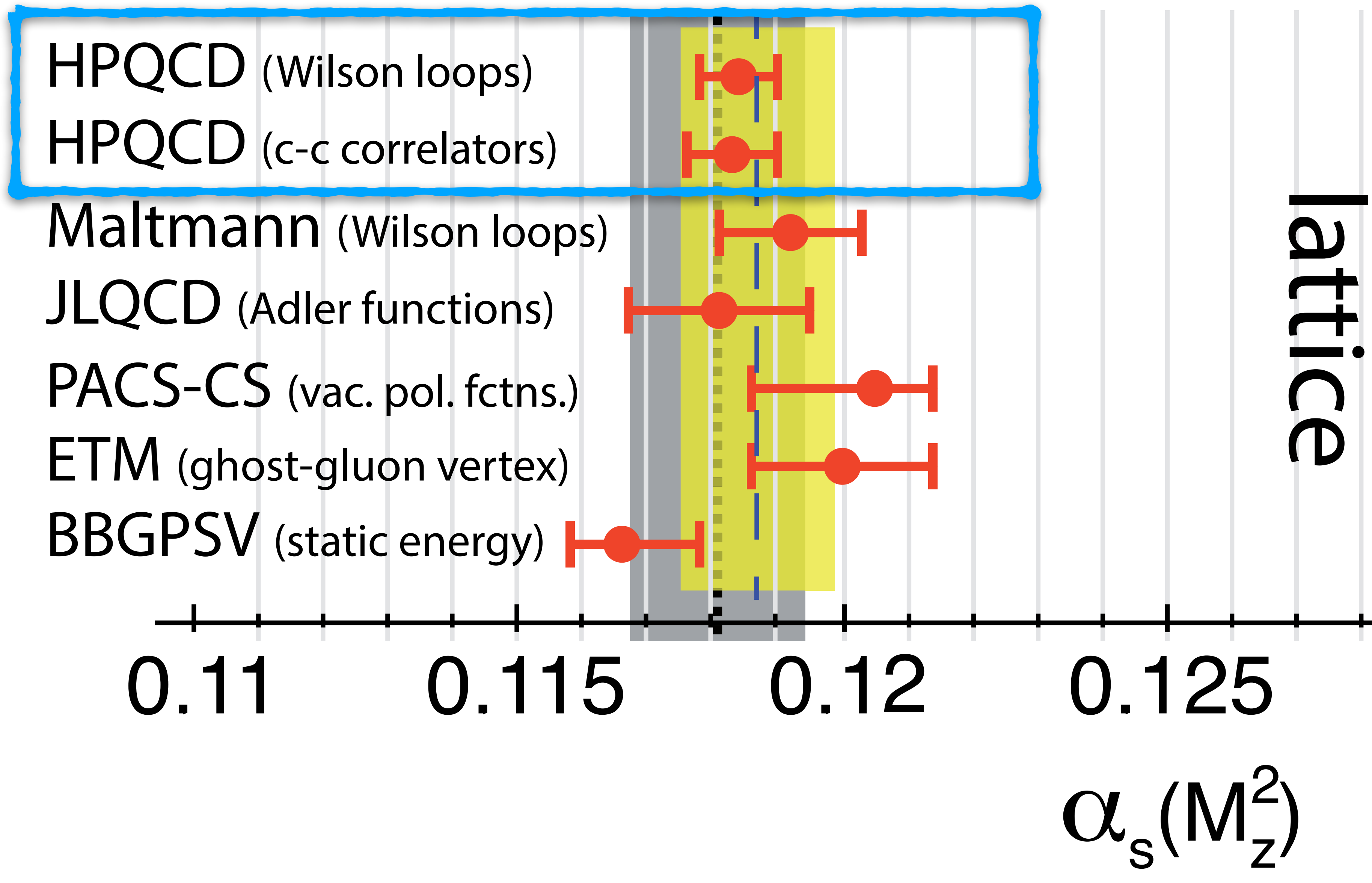
➤ Two best determinations are from same group (HPQCD, 1004.4285, 1408.4169)

$\alpha_s(M_Z) = 0.1183 \pm 0.0007$ (0.6%) [heavy-quark correlators]

$\alpha_s(M_Z) = 0.1183 \pm 0.0007$ (0.6%) [Wilson loops]

➤ Error criticised by FLAG, who suggest

$\alpha_s(M_Z) = 0.1184 \pm 0.0012$(1%)



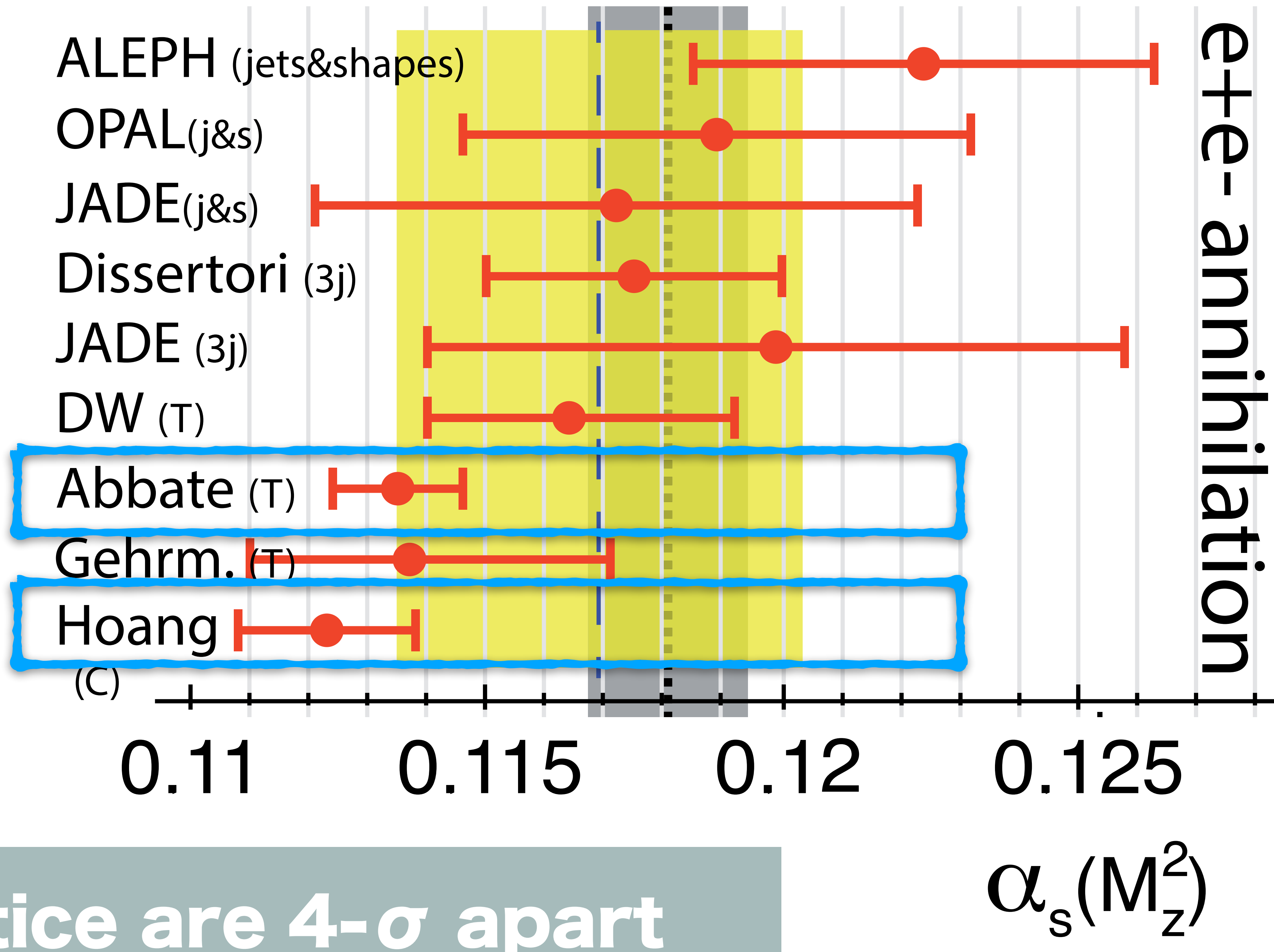
➤ Worries include missing perturbative contributions, non-perturbative effects in 3–4 flavour transition at charm mass [addressed in some work], etc.

➤ New ALPHA extraction (1706.03821) is cleaner in many respects

$\alpha_s(M_Z) = 0.1185 \pm 0.00084$(0.7%)

E+E- EVENT SHAPES AND JET RATES

- Two “best” determinations are from same group (Hoang et al, 1006.3080,1501.04111)
  $\alpha_s(M_Z) = 0.1135 \pm 0.0010\ (0.9\%)$ [thrust]
  $\alpha_s(M_Z) = 0.1123 \pm 0.0015\ (1.3\%)$ [C-parameter]



thrust & “best” lattice are 4-σ apart

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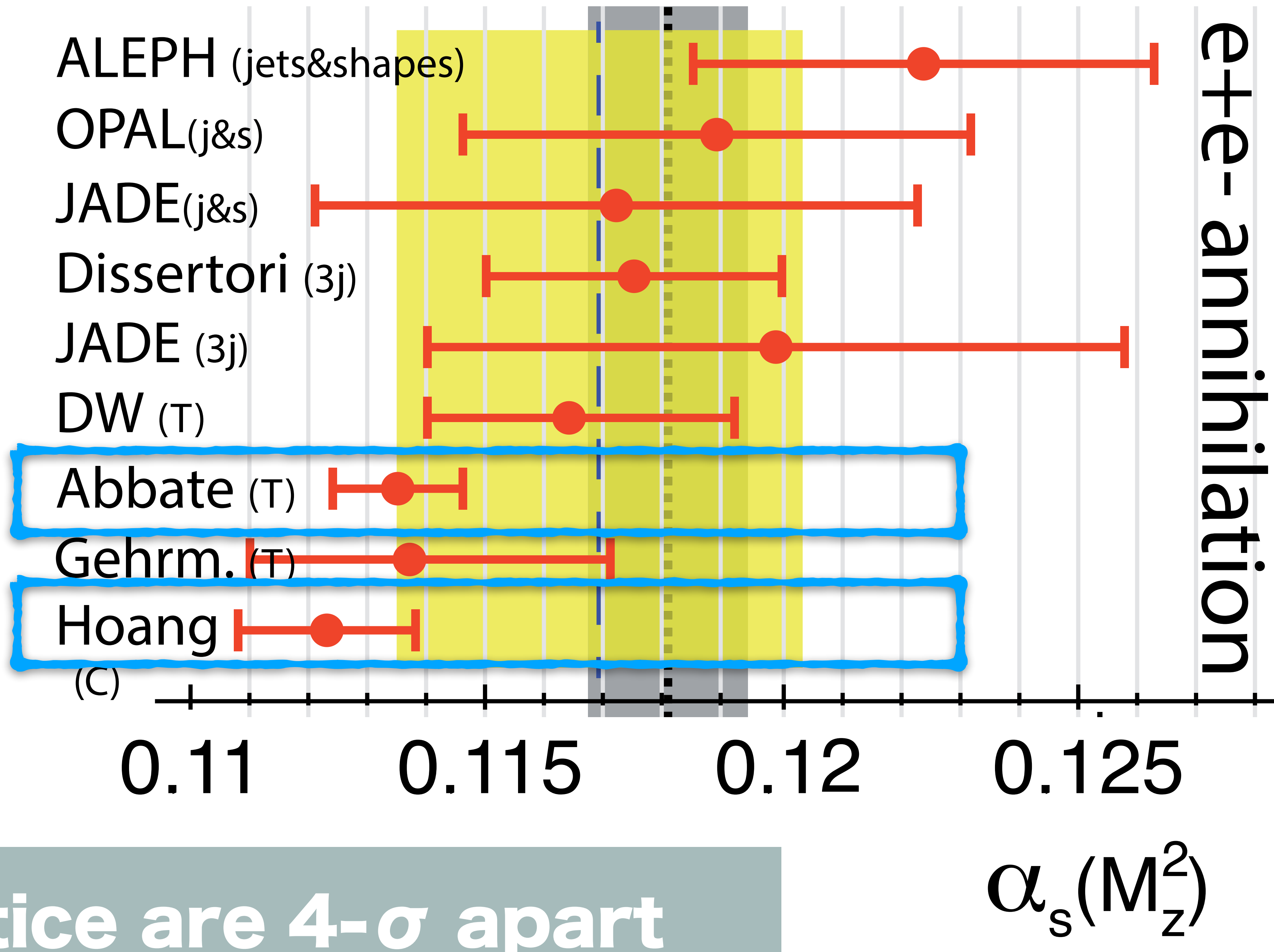
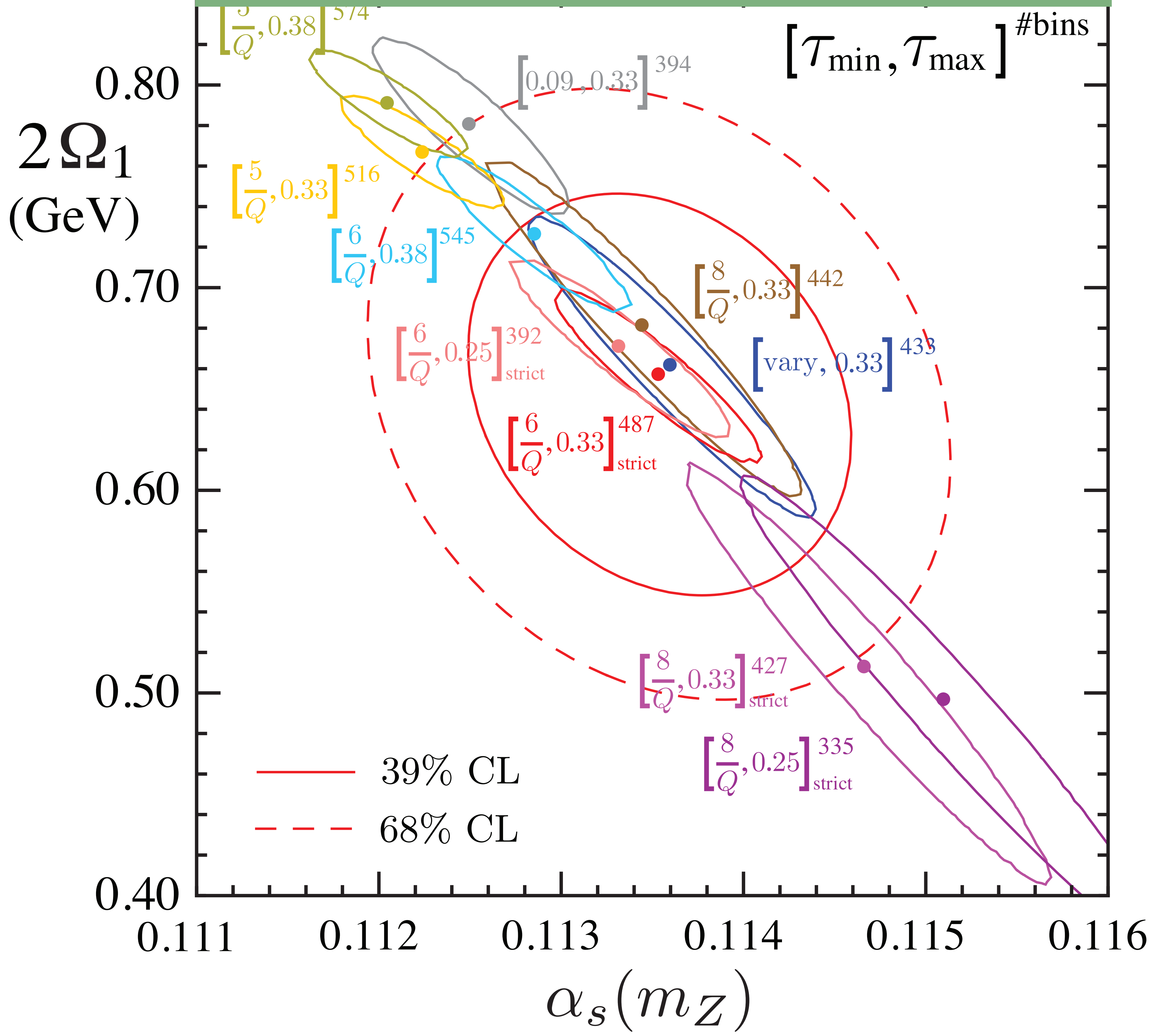


dependence on fit range



thrust & "best" lattice are 4-σ apart

<u>**Comments:**</u>

➤ thrust & C-parameter are highly correlated observables

➤ Analysis valid far from 3-jet region, but not too deep into 2-jet region — at LEP, not clear how much of distribution satisfies this requirement

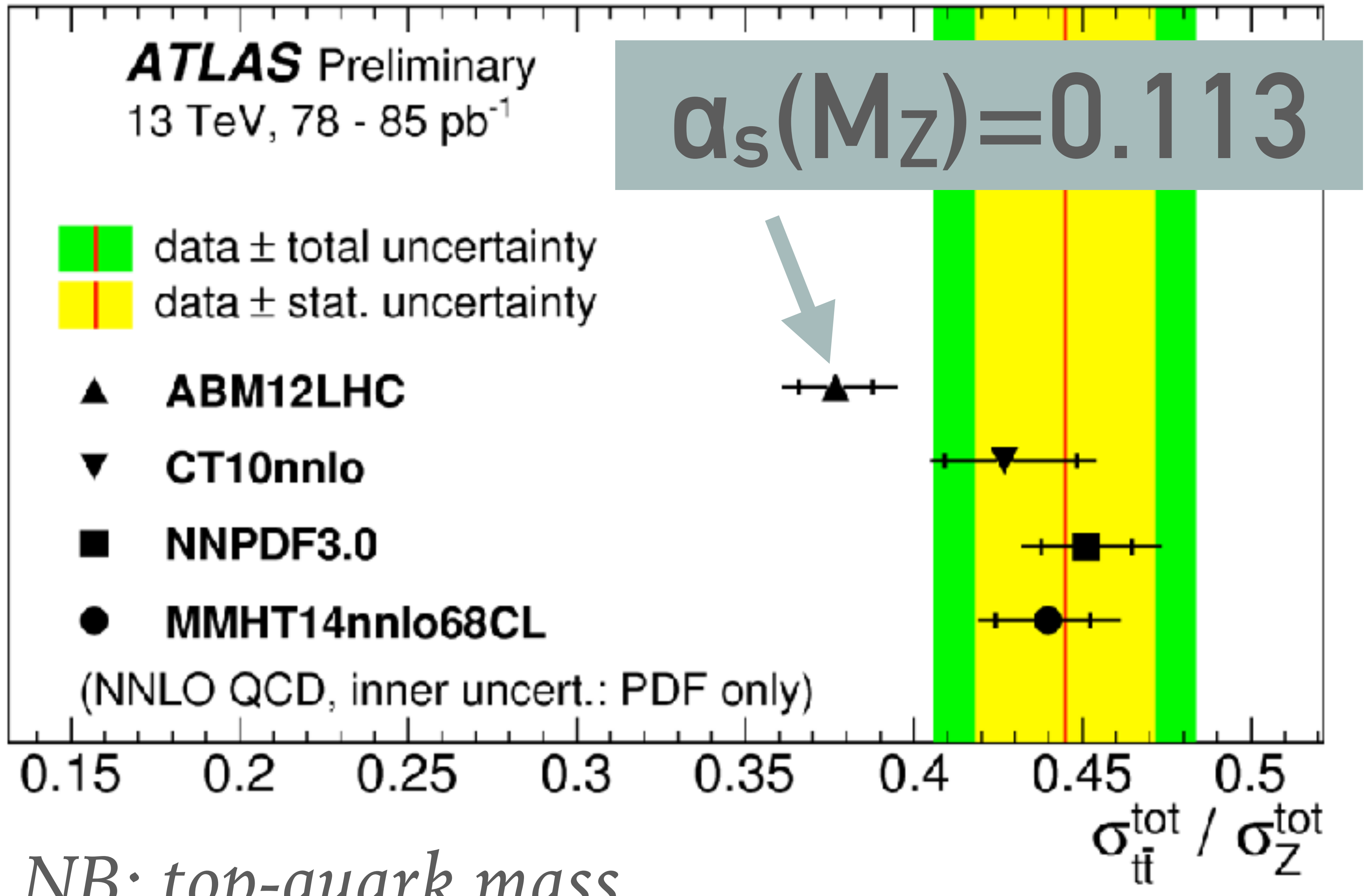
➤ thrust fit shows noticeable sensitivity to fit region (C-parameter doesn't)

WHAT WAY FORWARDS FOR α_s?

- We need to settle question of whether "small" (0.113) α_s is possible. LHC data already weighing in on this (top data), further info in near future (Z p_T, *cf*. later slides)

- To go beyond 1%, best hope is probably lattice QCD — on a 10-year timescale, there will likely be enough progress that multiple groups will have high-precision determinations

ATLAS-CONF-2015-049



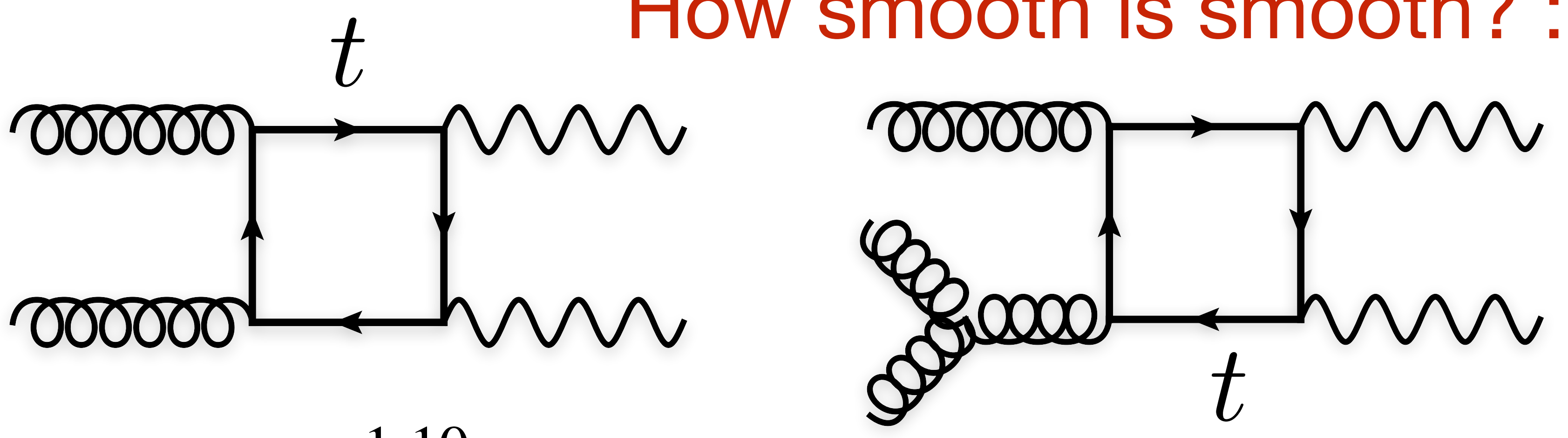
NB: top-quark mass choice affects this plot

DATA-DRIVEN BKGD ESTIMATES: NON-SMOOTHNESS AT 1% LEVEL

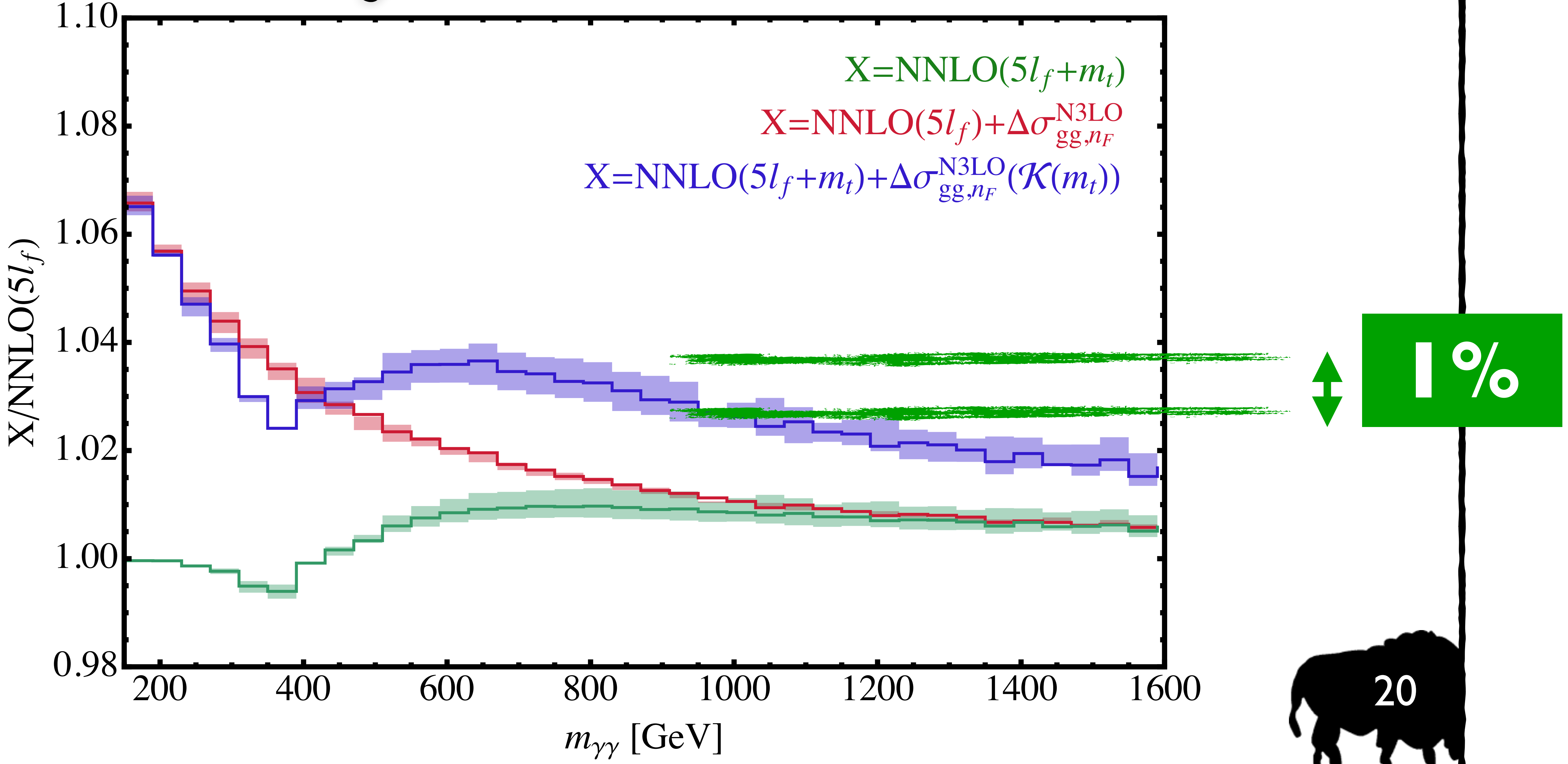
Predictions at high invariant masses.

As we all know, bump hunts in the diphoton system assume a smooth function which can be fitted to the data. Begging the question,

How smooth is smooth? :-)



C. Williams
Moriond QCD '16



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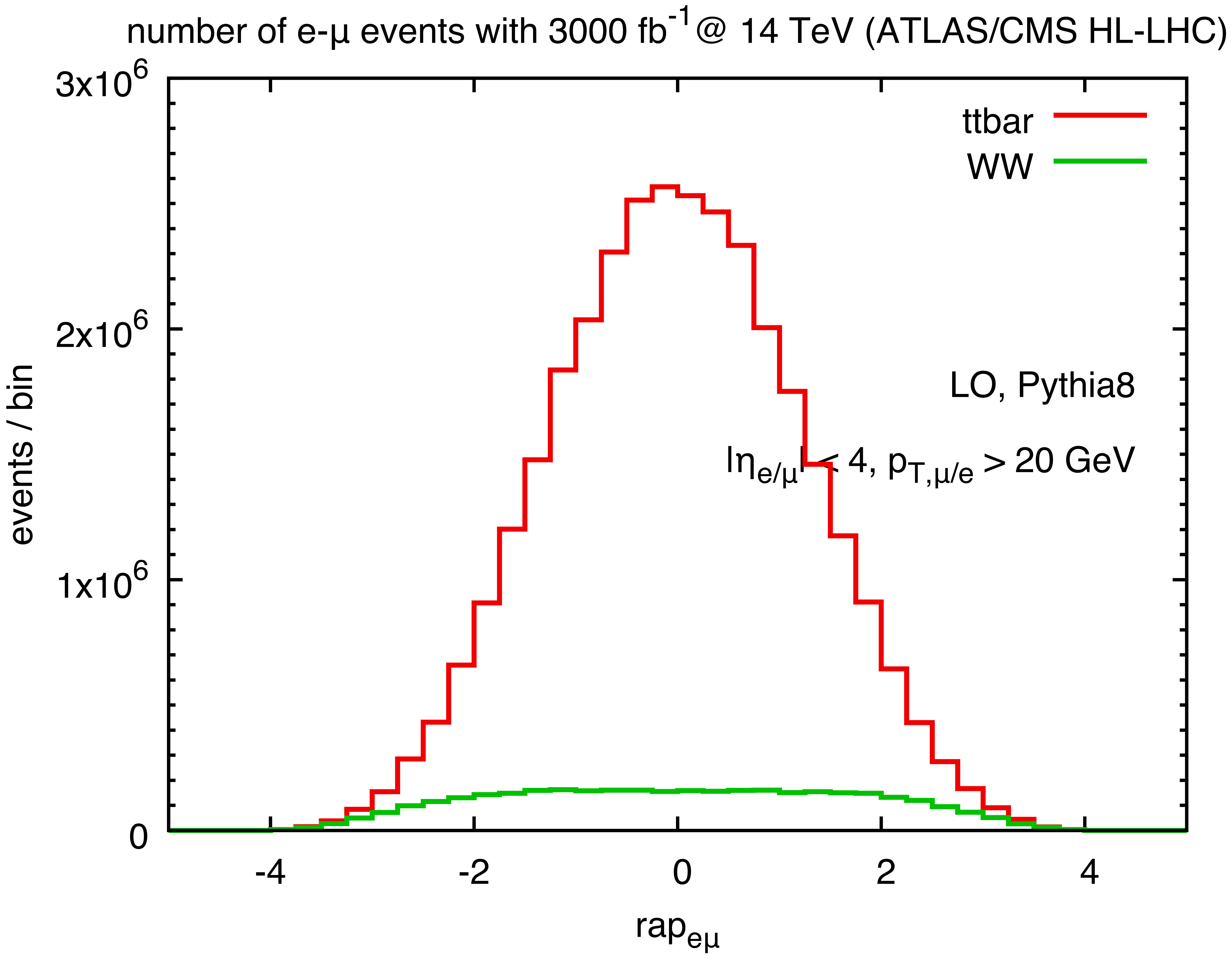
Standard experimental techniques, like data-driven bkgd estimates, can be skewed by O(1%) theoretical subtleties.

e-μ events (a mix of ttbar and VV) at HL-LHC ATLAS/CMS



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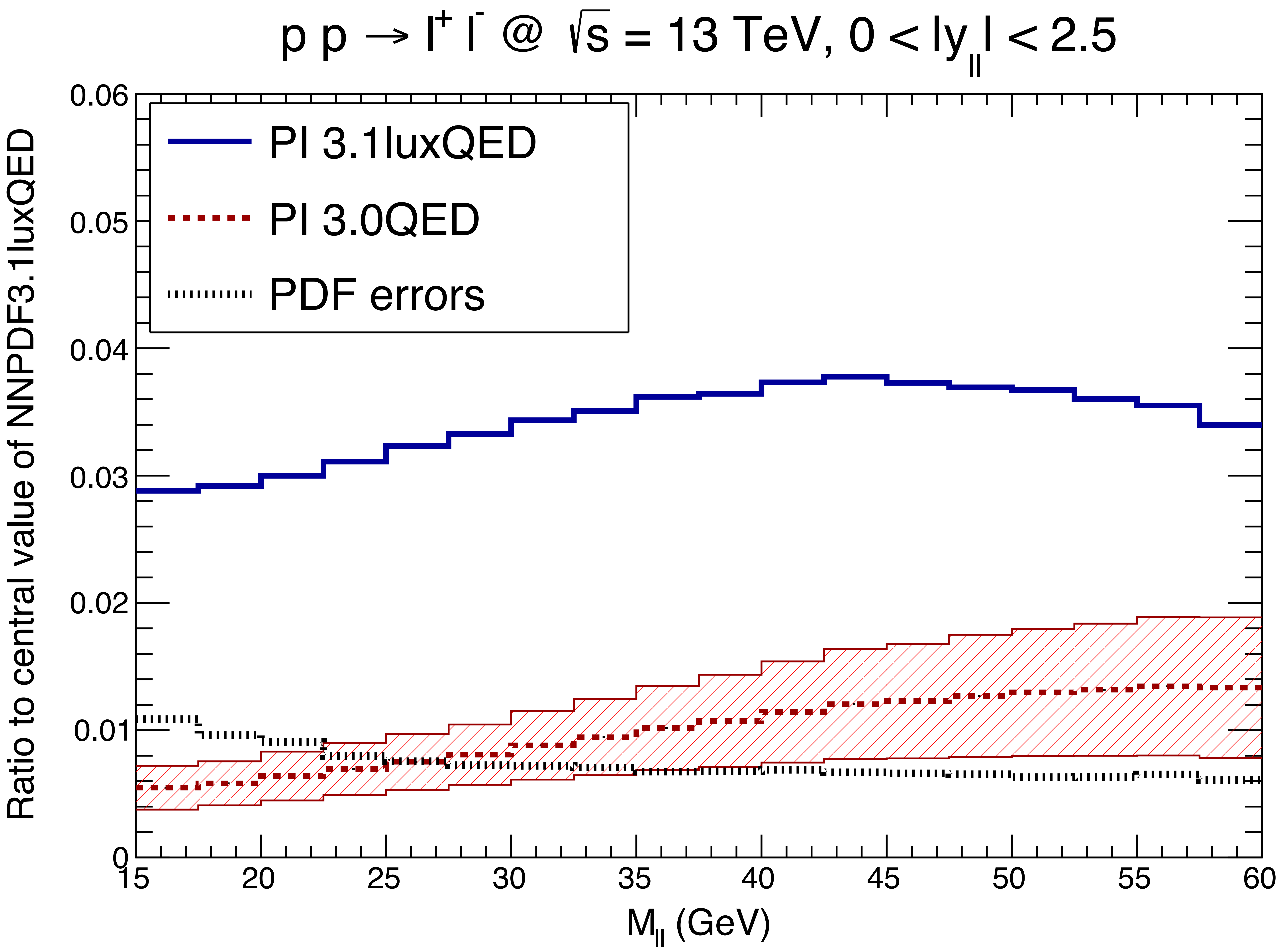
N(N)LO K-factors will increase rates significantly

there will also be other VV channels (probably smaller)

Photon PDF (NNPDF31luxQED, using Manohar, Nason, GPS & Zanderighi, 1607.04266)



barely any uncertainty on γγ-induced contribution

DY measurements can genuinely constraint other PDF contributions